DOCTOR OF PHILOSOPHY

Comparison of Epidermal and Dermal Fingerprints Collected from Thiel-embalmed Bodies

Dzetkulicová, Veronika

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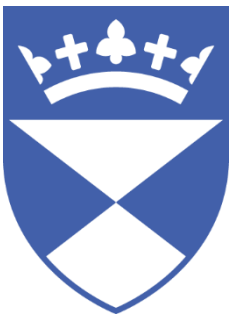

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Veronika Dzetkuličová, B.Sc. (Hons) M.Sc.

Leverhulme Research Centre for Forensic Science
School of Science and Engineering
University of Dundee

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List of Abbreviations

ACE-V. analysis – comparison – evaluation – verification

A.D. *anno Domini* (‘in the year of the Lord’)

AFIS. automated fingerprint identification system

B.C. before Christ

DNA. deoxyribonucleic acid

dpi. dots per inch

DR. dermal ridges

DVI. disaster victim identification

EDJ. epidermal-dermal junction

KID syndrome. keratitis-ichthyosis-deafness syndrome

RGB. red – green – blue

SL. *stratum lucidum*

SLR camera. single-lens reflex camera

SPA. Scottish Police Authority

SPSS. Statistical Package for the Social Sciences

TIFF. tagged image file format

UK. United Kingdom of Great Britain and Northern Ireland, also shortened as United Kingdom

U.N. GAOR. United Nations General Assembly Official Records

URN. unique reference number

USA. United States of America

USB. universal serial bus

Acknowledgements

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Declaration

I, Veronika Dzetkuličová, state that to the best of my knowledge, the content of this dissertation is my own work. Unless otherwise stated, all references cited have been consulted by me and the work of which the thesis is a record has been done by me. This work has not been previously submitted to any university for any other degree, diploma or qualification.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Signed: 

Date: 6th August 2020

Veronika Dzetkuličová
Dundee

Abstract

Direct comparison of dermal and epidermal fingerprints can be vital to the identification of bodies where the epidermal skin layer is no longer available for fingerprinting. It has been reported that identification based on the comparison between dermal and epidermal fingerprints is possible, however, there is limited research that supports this supposition. Epidermal desquamation occurs during the fixation of a body in Thiel embalming fluid providing an opportunity to compare dermal and epidermal fingerprints from one individual.

This study aimed to determine at which histological skin sublayer epidermal desquamation occurs in Thiel-embalmed bodies, to collect and compare dermal and epidermal fingerprints to understand which recovery method is optimal, to determine the accuracy with which these can be compared.

Tissue samples were collected from 40 individuals and fingerprints were collected from 67 individuals using black powder and photography pre and post embalming. Analysis of the tissue samples ensured that the prints recovered after embalming were dermal prints. Quality and minutiae analysis were performed by the author and by experienced fingerprint examiners (n = 16) from four countries on 80 fingerprint pairs (powder fingerprint pairs n = 40, photography fingerprint pairs n = 40).

There was a higher percentage of usable epidermal fingerprints recovered using black powder (91%) than using photography (72%). However, there was a lower percentage of usable dermal fingerprints recovered using black powder (64%) than using photography (81%). The results of the fingerprint comparison showed that fingerprint examiners were able to match a pair of fingerprints (identification) accurately in 10 to 15% of cases and they were able to establish fingerprint pairs as non-matching in 30 to 45% of cases.

Thiel-embalmed bodies offer a valid opportunity to study epidermal and dermal fingerprints collected from the same source. The collection, analysis, and comparison of epidermal and dermal fingerprint pairs should be approached by

fingerprint examiners with caution, especially in cases where the fingerprints are collected from elderly individuals.

Chapter 1 Introduction

Fingerprints have been used for identification purposes in the United Kingdom of Great Britain and Northern Ireland (UK) criminal justice system since 1900 (Henry, 1900; Berry and Stoney, 2001; Hutchins, 2011). Apart from the identification of potential suspects, fingerprints are also utilised as one of the primary identifiers in cases of unidentified bodies, both for individual cases or in events which have resulted in numerous casualties within disaster victim identification scenarios (Cattaneo *et al.*, 2006; Black *et al.*, 2010). The latest available Missing Person's Data Report of the National Crime Agency published in 2017 states that there were 45 bodies and 11 body parts reported by the UK police forces for that calendar year of which 47 cases in total were resolved by the time the report was published (National Crime Agency, 2019). The statistics do not include the percentage of cases in which fingerprints were utilised as the tool for identification. The consensus is that fingerprints are the least time-consuming of the primary identifiers available, if the condition of the body allows them to be recovered and therefore, are often employed in identification in favour of other primary identifiers [odontology comparison of dental records, analysis of deoxyribonucleic acid (DNA)] (Turner, 2013; Johnson and Riemen, 2019). It is still important to bear in mind, that identification of the deceased heavily depends on the availability and quality of the ante-mortem records as well as on the quality and availability of friction ridge skin of the deceased; for example in the case of the South east Asia tsunami in 2004, 31% of identifications were made via fingerprint comparison (De Valck, 2006; Morgan *et al.*, 2006; Interpol Tsunami Evaluation Working Group, 2007; Turner, 2013). In some cases, decomposition changes in bodies of the deceased may cause separation of the epidermis from the dermis, leaving only the deeper skin layer, dermis, attached to the body if the epidermis is completely degraded (Gill-King, 2006; Caruso, 2016). Even in such cases it may be possible to collect identifiable friction ridge prints from the dermal layer (Ferreira *et al.*, 2011; Mizokami *et al.*, 2015).

In theory, dermal fingerprints retain the same pattern of ridge detail characteristics as the epidermal fingerprints but sources dealing with the identification of bodies based on the comparison of epidermal and dermal fingerprints are scarce and often reliant on case studies of single individuals of

unknown ages (Plotnick and Pinkus, 1958). The age of the individuals is an important factor since with advancing age the dermal layer of the skin undergoes changes on its papillary surface impacting the clarity of any potential dermal fingerprints (Okajima, 1979). Despite the rarity of the cases where comparison of epidermal and dermal fingerprints is required, such cases are encountered in practice and the most current research advises a cautious approach and acknowledges challenges encountered when comparing epidermal and dermal fingerprints (Turner, 2013; Mizokami *et al.*, 2015). This study, therefore, attempts to contribute to the field of epidermal-dermal fingerprint comparison by bringing in data from a larger sample size of elderly individuals with a hope to eventually create a source of epidermal-dermal fingerprint data available to researchers and practitioners. Additionally, among one of the fingerprint evidence areas which need to be researched, the Forensic Science Regulator of England and Wales recommends studying the permanence of ridge detail (Forensic Science Regulator, 2020). With a broad perspective, the topic of this thesis fits the suggested area. Even though the Forensic Science Regulator does not mention the problem of ridge detail changes post-mortem, the loss of epidermis and subsequent exposure of the dermis can nevertheless be a drastic change to the landscape of friction ridge details. This thesis studies the differences between the epidermal and dermal fingerprints of elderly individuals and explores fingerprint collection techniques that would ensure the capture of ridge details in the dermal skin layer to maximise its identification potential.

The model for the collection of epidermal and dermal fingerprints were bodies embalmed according to the method of Walter Thiel, a process during which the bodies undergo epidermal desquamation (Eisma *et al.*, 2011). Thiel-embalmed bodies offer an opportunity of studying epidermal and dermal fingerprints from a known source without the need for amputation of digits and/or any further chemical treatment. Although the dermal fingerprints from Thiel-embalmed bodies do not cover the full range of challenging conditions that may be encountered by professionals collecting fingerprints from the deceased, this model offers an opportunity to collect dermal fingerprints from an oily skin surface occasionally with partially or fully desiccated digits.

This thesis consists of six chapters. The second chapter of the thesis reviews relevant literature sources and introduces definitions and concepts important for later chapters. The chapter is split into two main sections. The first describes attributes of normal friction ridge skin as well as changes occurring to this region of the human body during the life of an individual as well as post-mortem. The second part discusses the utilisation of friction ridge skin as an identifier. The historic and current uses and procedures of identification are described mainly from the perspective of the United Kingdom. The uses and limitations of dermal friction ridge skin in forensic identification processes are also discussed.

The third chapter contains the first experimental part of the thesis. The experiment aims to confirm that the dermal skin layer in the areas of friction skin is exposed as a part of the embalming process in Thiel-embalmed bodies. The epidermal desquamation process is followed for four to six weeks post-immersion into embalming fluid and histological friction ridge skin sections are sampled weekly from 20 individuals. Friction ridge skin layers observed in sampled histological sections are described and compared to sections taken before the embalming. The experimental results are discussed within the framework of existing literature, highlighting also the limitations of the study. Possible avenues of future research in the area of epidermal desquamation in Thiel-embalmed bodies and its uses within the fingerprint context are also included.

Since the first experiment confirmed exposure of the dermal friction ridge skin layer, the collection of epidermal and dermal fingerprints from the same individuals was deemed possible. The fourth chapter describes the collection and baseline analysis of epidermal and dermal fingerprints collected using black granular powder and digital photography. The chapter further describes the analysis of a subsample of collected fingerprints by 16 trained fingerprint examiners from four countries and the results of the comparison of epidermal-dermal fingerprint pairs performed by these experts. The results of all analyses (baseline and expert analyses) are also discussed within the wider context of available literature. Limitations of the study are acknowledged and suggestions for future research are explored.

The last chapter consists of discussion highlighting important findings from the previous two chapters. The generic discussion brings together the main conclusions of the thesis' experimental parts highlighting contributions to the community of forensic scientists and practitioners. It is hoped that this work's data will contribute to more effective processes of identification in cases of unidentified bodies, so a right to identity of the deceased can be upheld and a measure of closure and peace can be gained by those who are waiting for the information.

1.1 Aims and objectives

Through histological observation of skin samples collected from bodies before and at multiple time points during the process of Thiel embalming, this project aims to describe when and at what epidermal skin sublayer could epidermal desquamation be observed in friction ridge skin of thumbs.

With the purpose to establish whether post-mortem dermal fingerprints collected from unidentified bodies could be used for identification purposes when compared to ante-mortem epidermal fingerprints, the further aim of this project is to compare the quality, usability, and comparability of epidermal and dermal fingerprints collected from Thiel-embalmed bodies. Furthermore, through employing two different fingerprint collection techniques, black powder and photography, this project also aims to establish which of the collection techniques would be more suitable to collect higher quality epidermal and dermal fingerprints from Thiel-embalmed bodies. Lastly, through creating a ground truth database of epidermal and dermal fingerprints collected from Thiel-embalmed bodies this project aims to create a training resource for fingerprint examiners and future researchers to enhance the knowledge and experience in the fields of identification of deceased individuals and disaster victim identification (DVI).

Chapter 2 Literature review

2.1 Skin anatomy and physiology

The skin is the organ with the largest surface area within the human body (Tortora and Derrickson, 2009). It interacts directly with the environment and is the first line of physical protection against foreign organisms, radiation and other particles (Jablonski and Chaplin, 2010; Baroni *et al.*, 2012). Apart from participating in the human immune system and involvement in the production of vitamin D, it also acts in temperature regulation of the human body which is closely connected to the excretion of waste products (Powell, 2006; Jablonski and Chaplin, 2010). Another vital function of the skin is participation in somatosensation via touch and pain receptors (Metze and Luger, 2001).

The skin has three main layers: epidermis on the surface, dermis in the centre and the deepest layer – hypodermis, which is also referred to as the subcutis (Figure 2.1.1).

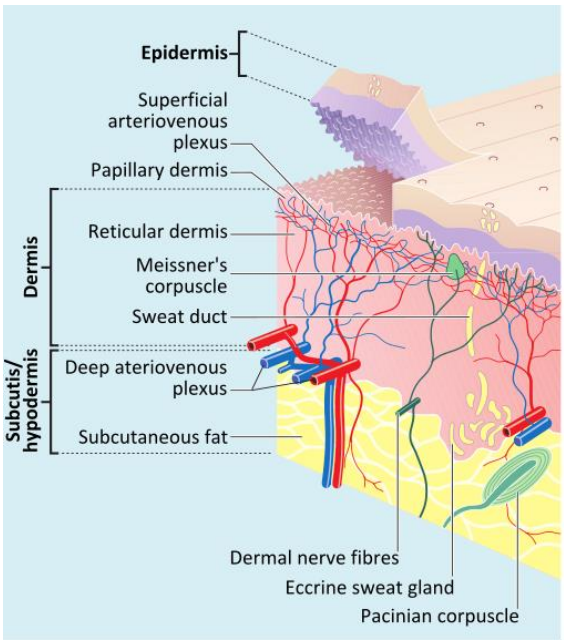

Figure 2.1.1 Schematic of the structure of thick skin. Adapted from https://en.wikipedia.org/wiki/File:Skin_layers.png under the license CC BY-SA 3.0, authored by Madhero88 and Komorniczak (2012).

The epidermis is composed of five sub-layers (Figure 2.1.2) which contain several different types of cells (Maceo, 2011). The overall thickness of the epidermis

varies depending on the area of the body and can be between 0.22 mm and 0.55 mm in depth (Bossen *et al.*, 2010). The deepest of the sub-layers is known as the *stratum basale* (Figure 2.1.2) which is in contact with the dermis and produces new cells that are pushed to the surface whilst differentiating into keratinocytes (90 – 95% of all cells in the epidermis) (Haake *et al.*, 2001). The keratinocytes also undergo cornification on their way to the surface when they become part of the *stratum corneum* which is a top layer of the epidermis constantly being shed and replaced by new cells (Milstone, 2004). Other cell types present in the epidermis are: melanocytes (responsible for protective pigment production and vitamin D synthesis), Langerhans cells (initiating immune responses) and Merkel cells (transmission of touch sensation) (Haake *et al.*, 2001; Junqueira and Carneiro, 2003). The basement membrane zone is an area of junction between the epidermis and dermis (Woodley and Chen, 2001). The component of the epidermis in the junction is *lamina lucida* (composed of hemidesmosome anchor filaments projecting downwards), whilst dermis contributes *lamina densa* (collagen fibres interwoven with hemidesmosome anchor filaments) and *sublamina densa* (elastic fibres, additional collagen fibres, and anchoring plaques interwoven with fibres of *lamina densa*) (Woodley and Chen, 2001).

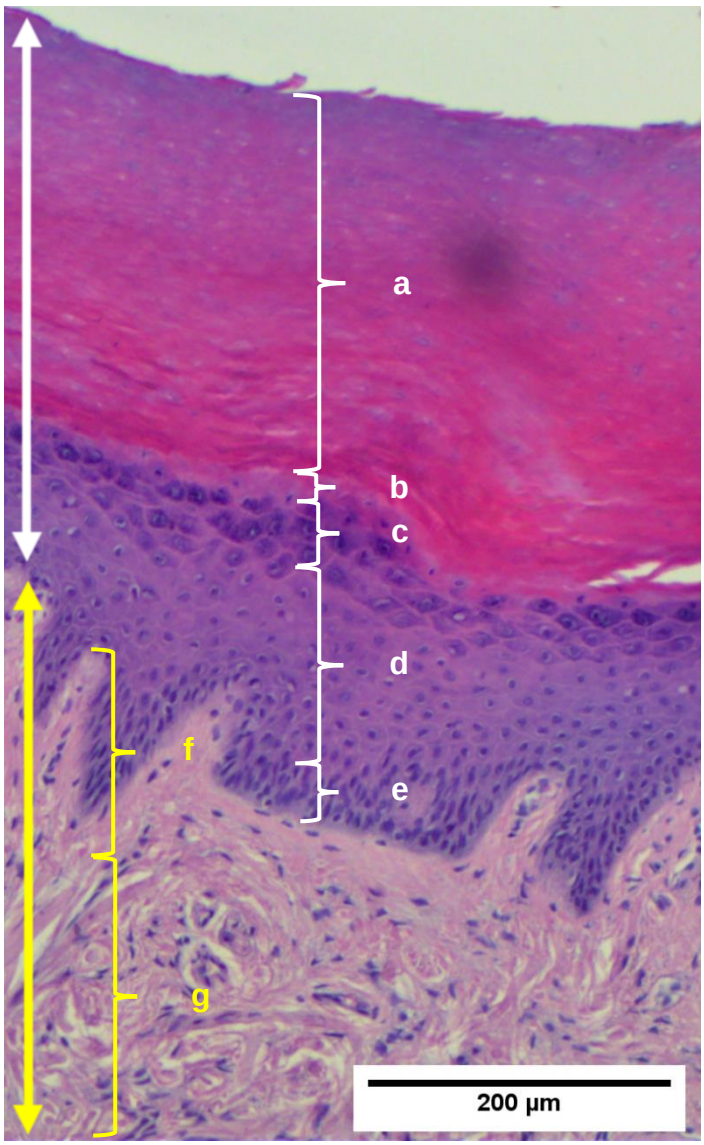

Figure 2.1.2 Light micrograph of epidermal and dermal thick skin sublayers. Section stained with haematoxylin and eosin. White double-headed arrow = epidermis, yellow double-headed arrow = dermis. a – *stratum corneum*, b – *stratum lucidum*, c – *stratum granulosum*, d – *stratum spinosum*, e – *stratum basale*, f – papillary dermis, g – reticular dermis.

The dermis lies beneath the epidermis and has a thickness of about 2 – 5 mm (Oltulu *et al.*, 2018). It is composed of two layers – papillary and reticular (Figure 2.1.2). A papillary dermal layer is composed of loose connective tissue which is anchored to the epidermis via anchoring fibrils and epidermal anastomoses (Haake *et al.*, 2001; Powell, 2006). The papillary dermal layer also contains dermal cells and dermal papillae (peg-like projections of the dermis) (Chacko and Vaidya, 1968). Dermal papillae respond to shearing forces that influence skin daily which in turn has an impact on the remodelling of the dermal layer with increasing age; this will be discussed in more detail in the later sections of the literature review (sections 2.3.1 and 2.6.1) (Hale, 1952; Chacko and Vaidya,

1968; Misumi and Akiyoshi, 1984). Each dermal papilla has blood supplied to it via a dermal papillary loop of vascular tissue which branches from and feeds to a vascular plexus situated between the papillary and reticular dermis (Junqueira and Carneiro, 2003; Sangiorgi *et al.*, 2004). Moreover, dermal papillae also contain free nerve endings (present in each of the papillae, responsible for rapid response stimuli) and Meissner corpuscles (touch receptors, found in about every fourth papilla) (Dillon *et al.*, 2001; Metze and Luger, 2001). Other sensory receptors found in the dermis outside of dermal papillae are Pacinian and Ruffini corpuscles which participate in pressure transmission (Metze and Luger, 2001). There are also autonomic nerve branches innervating vascular structures and sweat glands (Metze and Luger, 2001).

A reticular dermal layer is composed of dense connective tissue containing large amounts of collagen and elastic fibres responsible for the strength and resilience of the layer and connection of the dermis to the hypodermis (Haake *et al.*, 2001). The reticular dermal layer contains the majority of the blood vessels in the skin; it shares one arterial plexus with the papillary dermal layer and one with the hypodermis. Two venous plexuses are corresponding to the arterial ones, but there is also an extra venous plexus solely in the reticular dermal layer (Junqueira and Carneiro, 2003; Sangiorgi *et al.*, 2004). Furthermore, the reticular dermal layer partially hosts embedding of sweat glands (Hurley, 2001).

The hypodermis is the deepest layer of the skin and its thickness depends on the area of the body and individual's reservoir of subcutaneous fat (Haake *et al.*, 2001; Maceo, 2011). It is attached to the dermis via interlocking fibrous components of the reticular dermal layer and contains adipose tissue for stress absorption, movement of the skin over deeper structures of the body, thermoregulation, and as an energy source. It also shares blood vessels, nerves and the embedding of sweat glands with the dermis (Hurley, 2001; Metze and Luger, 2001; Singh and Swerlick, 2001).

2.2 Friction ridge skin

2.2.1 Anatomy

Friction ridge skin is the term used for specialised parts of the skin composed of ridges and furrows (in some literature called valleys) visible on the outermost skin surface (Maceo, 2011). According to Maceo (2011), the outer morphology of the friction ridge skin is dictated by its function, where the ridges and furrows facilitate an ability to grasp and the creases in the skin allow flexion of the skin to occur. Penrose and Ohara (1973) argue that friction ridge skin is an evolutionary remnant which helped our arboreal ancestors exercise a firm grip in tree branches.

According to Maceo (2011), the underlying structure of friction ridge skin develops in the dermal skin layer, where dermal papillae are situated underneath the epidermal ridges and provide patterning, support and strength to the epidermal friction ridge skin (Figure 2.2.1). The spatial organisation between the epidermal and dermal ridge/papillary formations can vary according to the age of an individual and between various locations within the human palm and foot sole as proven by Chacko and Vaidya (1968). They describe three types of dermal papillae arrangements into dermal ridges (DR) which can be related to the surface epidermal ridges in friction ridge skin (Figure 2.2.2).

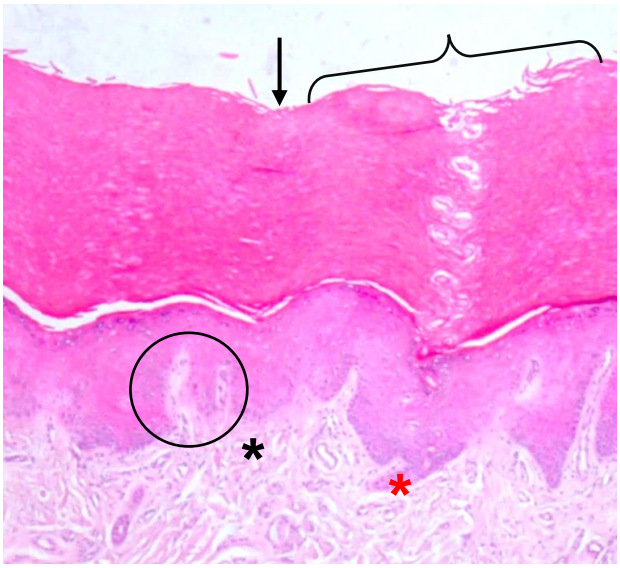

Figure 2.2.1 Micrograph showing friction ridge skin epidermal and dermal structures. Section stained with haematoxylin and eosin. Black circle = dermal papillae, black asterisk = dermal furrow, red asterisk = dermal groove, bracket = epidermal ridge, black arrow = epidermal furrow.

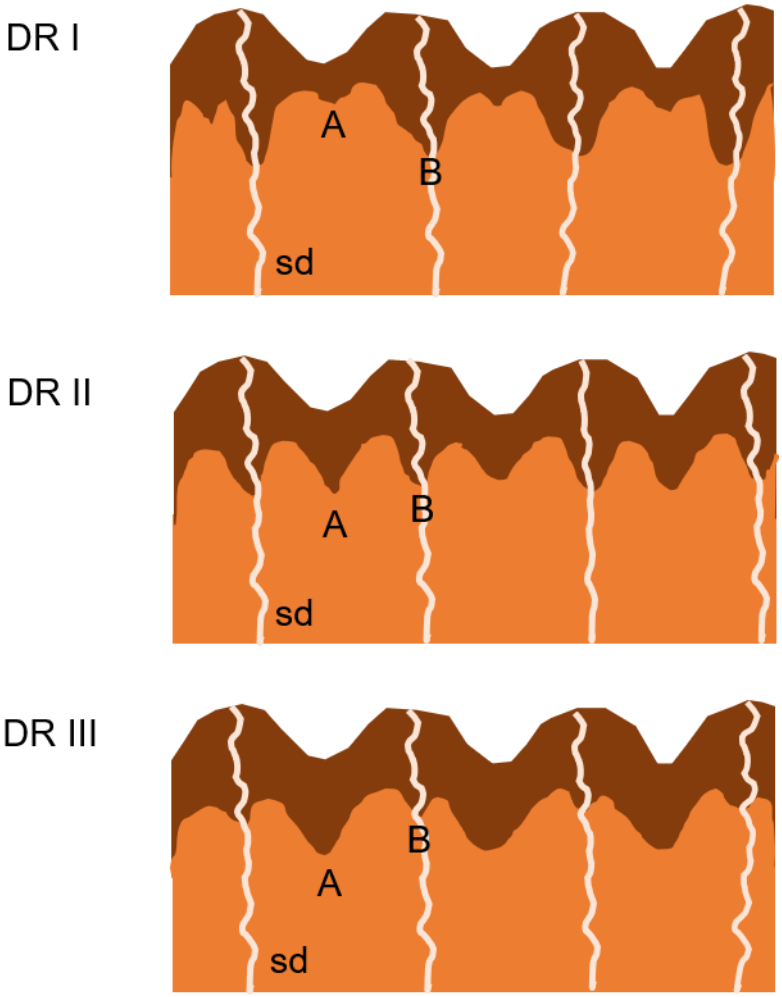

Figure 2.2.2 Drawing illustrating arrangements of dermal ridges (DR) as related to the epidermal ridges according to Chacko and Vaidya (1968). A – dermal furrow (limiting groove in original publication), B – dermal groove (intermediate groove in original publication), sd – sweat duct. Adapted from Chacko and Vaidya (1968).

The three types of arrangements were labelled DR I, DR II, and DR III and are separated by the appearance of dermal papillae in relation to the depth of dermal furrow and dermal groove. Chacko and Vaidya (1968) report DR III was the type of arrangement observed most often in the human adult friction ridge skin yet the other two types were also observed in adult specimens, however, only DR I and II types of arrangements were observed in human new-borns (Figure 2.2.2). This finding makes other sources of literature which describe friction ridge skin clearer, since other papers that report the structure of epidermal and dermal friction ridge skin tend to sample and subsequently describe only one of the papillary arrangement types arguing this is how the dermis is organised in relation to the epidermis in friction ridge skin. However, by relating these back to the work of Chacko and Vaidya (1968), it is possible to understand which of the three types

of organisation these samples fit into (Plotnick and Pinkus, 1958; Penrose and Ohara, 1973). Furthermore, there is also an array of nomenclature versions for grooves/furrows/cristae present around the dermal papillae (Table 2.2.1). To maintain clarity throughout the present text, the nomenclature of dermal furrow (structure A) and dermal groove (structure B) was chosen to describe the appearance of the dermal layer of friction ridge skin (Figure 2.2.2).

Table 2.2.1 Nomenclature of dermal skin structures from Figure 2.2.2 as mentioned in various publications.

Reference	Structure A	Structure B
Plotnick and Pinkus (1958)	No specific name	deep intermediate crista
Chacko and Vaidya (1968)	limiting groove	intermediate groove
Penrose and Ohara (1973)	furrow fold (from the perspective of the epidermis)	glandular fold papilla (from the perspective of the epidermis)
Okajima (1975, 1979, 1984)	furrow	groove
Misumi and Akiyoshi (1984)	furrow	groove

Due to the specialisation of friction ridge skin, there are differences not only at the morphological level but also in cellular and sub-cellular structures. Cells from the *stratum basale* that sit above dermal papillae and grooves firstly divide into transient amplifying cells which multiply many times and only then will these new cells enter the *stratum spinosum* to be further differentiated (Lavker and Sun, 1982, 1983). The cells in the basal layer underlying the epidermal friction skin furrows divide continuously and each new cell is immediately pushed into the *stratum spinosum* to undergo further differentiation (Lavker and Sun, 1982, 1983). This variability in division occurs because the epidermal friction skin ridges need more cellular layers to maintain their height due to pronounced abrasion compared to the more shielded cells in the epidermal friction furrows. The morphology of the junction between the basement membrane and basal keratinocytes is further evidence of the latter's differential function. The dermal furrows' basal keratinocytes have long projections extending into the dermis which serve as anchors. This compares to the basal keratinocytes of the dermal papillae and grooves which have only a slightly undulated junction with the

basement membrane as they function more like stem cells when they multiply by demand (Lavker and Sun, 1982, 1983).

Another example of cellular differences in friction ridge skin is the variable expression of keratin. Keratinocytes of friction ridge skin express different types of keratin when compared to other keratinocytes in non-friction ridge skin (Swensson *et al.*, 1998). Epidermal cells covering the dermal papillae and dermal grooves produce more durable keratin, whereas the cells covering dermal furrows contain less stress-resistant keratin. This arrangement results in the stiffening of surface epidermal ridges and hinge-like pliability of furrows, allowing them to withstand the compression forces applied to this type of skin (Swensson *et al.*, 1998). According to Wan *et al.* (2003), the desmosomes (connecting elements between keratinocytes of the basal layer) are larger and stronger in friction ridge skin than in the rest of the skin, and the basal keratinocytes of friction ridge skin are also larger containing a greater density of keratin which is linked to a greater amount of stress friction ridge skin is exposed to.

The friction ridge skin also contains the highest concentration of sweat glands compared to other areas of the skin (Hurley, 2001). The sweat glands are anchored in the hypodermis and dermis and have ducts that pass through the dermal grooves and reach the epidermis bringing the sweat onto the surface via sweat pores (Hurley, 2001).

2.2.2 Development *in utero*

The timing of the development of ridge detail varies. Penrose and Ohara (1973) argue that the whole process of ridge and furrow formation takes place between the 2nd and 5th month of foetal life. Kücken and Newell (2005) and Kücken (2007) established crucial moments for fingerprint formation between the 10th and 16th week of pregnancy. Okajima (1975) reports the start of dermatoglyphic development in the 6th week. Since he looked specifically at the dermal layer, there is no completion time reported in relation to the development of dermal papillae dermatoglyphic features. This is due to the existence of evidence of continual development or alteration of this layer throughout life discussed in later sections 2.3.1 and 2.6.1 (Fleischhauer and Horstmann, 1951; Kücken, 2007).

No matter where it occurs, the formation of ridge detail characteristics is closely connected to the embryonic formation of volar pads (Figure 2.2.3). These are temporary eminences of subcutaneous tissue and fat present around distal phalanges (apical pads) and in palmar/plantar region (interdigital, thenar and hypothenar pads) which form between the 7th and 10th week *in utero* (Cummins, 1929; Sadler, 2010). Volar pads on the soles of the feet start developing later and are present longer than those on hands (Okajima, 1975, 1979). According to Wertheim and Maceo (2002) and Kücken and Newell (2005), the 'bulginess' and symmetry of pads will later influence ridge pattern type, which was a concept first time suggested and validated by the work of Babler (1987, 1991)

Figure 2.2.3 Schematic representation of volar pads present on the palmar surface of the human hand during foetal development. Drawn according to images from Jirásek (1983).

The formation of friction ridge skin is initiated on the interface between the dermal and epidermal layer (Okajima, 1975, 1979). The innermost epidermal layer (basal layer) becomes undulated between week 10 and 13 *in utero* (Babler, 1991; Kücken and Newell, 2005). The undulations become more prominent and form primary dermal ridges and grooves which will then define the pattern of epidermal ridges (Figure 2.2.4) (Okajima, 1975; Kücken, 2007). Bonnevie (1927) and Schaeuble (1932) also report the rapid proliferation of cells and the appearance of a small patch of ridges on volar pads' epidermal skin surface during this period.

They call the patch ‘ridge anlage’ which often coincides with cores of ridge patterns on the first level of fingerprint characteristics.

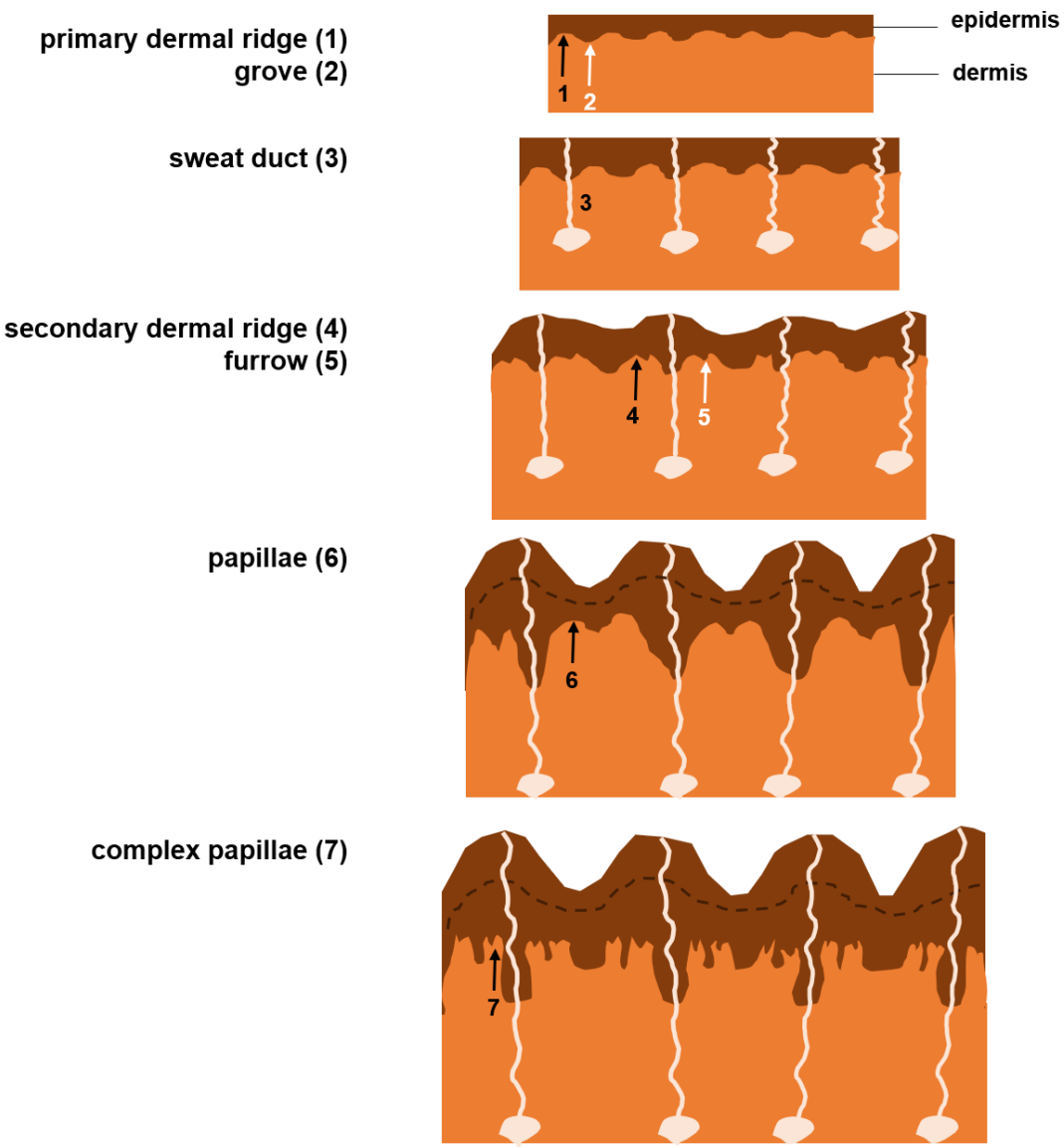

Figure 2.2.4 Diagram illustrating the development of dermal skin layer. The dashed line divides the keratinised epidermal layer (upper layer) from the rest of the epidermis. Adapted according to Okajima (1975).

Sweat duct formation commences in the 14th week *in utero* (Okajima, 1975; Kücken, 2007). This occurs as a downward projection from the dermal groove which is between the primary dermal ridges (Figure 2.2.4). According to Hirsch and Schweichel (1973) and Wertheim (2011), it is the formation of sweat ducts together with increased proliferation pressure from cells creating primary ridges that help to push the ridge pattern to the epidermal surface. By the end of the 19th week of intrauterine development, the primary dermal ridge formation stops and

secondary dermal ridges start to form (Figure 2.2.4) (Okajima, 1975; Kücken, 2007). Secondary dermal ridges are shallow folds dividing the primary dermal ridges into a double row of ridges with dermal furrow between them (Figure 2.2.4) (Okajima, 1975). From these secondary dermal ridges, dermal papillae are formed (Figure 2.2.4) (Okajima, 1975). Dermal papillae are peg-like protrusions of dermal skin layer into the epidermal layer above, their formation commences by the 24th intrauterine week, and they become more complex with increasing age (Figure 2.2.4) (Misumi and Akiyoshi, 1984; Kücken, 2007).

The human body develops as a result of genetic and environmental interactions. Friction ridge skin is no exception from this rule. However, there are several theories regarding the formation of friction ridge skin. According to Maltoni *et al.* (2009) and Burger *et al.* (2011), the developmental principles of friction ridge skin resemble those of blood vessel formation; genetic information is responsible for general skin differentiation and encodes predispositions for ridge formation, but the uterine microenvironment (amniotic fluid flow) and foetal movements and position influence the formation of individualising characteristics. The study of Jain *et al.* (2002) reports that monozygotic twins have highly similar first-level fingerprint characteristics but differ in second-level minutiae fingerprint characteristics. Theories in the literature vary about the driving mechanism behind the individual differences in friction ridge skin. Wertheim (2011) describes increased ridge pattern formation connected to the rapid growth of the extremities *in utero*; the process of rapid ridge multiplication is then responsible for the formation of second-level minutiae characteristics. Some theories propose an influence caused by the rapid growth of the digits, others describe differential chemical (hormonal) regulation as being responsible for individual variation (Hale, 1952; Smith and Holbrook, 1986). The most recent theory is based on mechanical compressive forces of rapidly proliferating cells resulting in a buckling instability in the basal epidermal layer which results in ridging of the dermis and formation of surface friction ridge skin characteristics (Kücken and Newell, 2005; Kücken, 2007).

Kücken (2007) further describes changes occurring to the epidermal surface of friction ridge skin. Apart from the already formed ‘ridge anlage’, there are two other patches of epidermal ridge formation, one being close to the nail furrow and

the other called basal ridges close to the proximal part of the distal phalanx. According to Kücken (2007), when these three groups contact each other they form second level minutiae characteristics and first-level deltas (triradii). It is further suggested that the formation of friction ridge skin, namely its second-level characteristics, is influenced by the distribution of the epidermal Merkel cells which impact stress distribution throughout the epidermis and contribute to friction ridge skin pattern formation (Kücken and Champod, 2013).

2.3 Friction ridge skin alterations

According to Kücken (2007), after about seven months of intra-uterine development fingerprints are fully formed and do not change pattern configuration throughout life therefore possessing the attribute of persistence, which in turn fulfils one of the requirements of a biometric characteristic (Jain *et al.*, 2000). As mentioned above, the pattern persists, firstly due to the physical attachment that is present between and within individual skin layers and secondly due to the regulation of cell proliferation/inhibition. Although the arrangement of the epidermal friction ridge skin does not change and the ridges and furrows maintain their positions, it is known that the properties of skin in general change both with ageing and under the influence of various circumstances such as diseases, accidents or occupation; this can subsequently be observed also in a very slight alteration of friction ridge skin (Nagesh *et al.*, 2011; Wertheim, 2011; Tobin, 2017).

2.3.1 Age-related changes

Albeit on a small sample of two individuals, Sir Francis Galton observed age changes to friction ridge skin in juvenile individuals. He collected fingerprints from a two-year-old and an eight-year-old child and followed up with fingerprint collection from the same individuals subsequently after 13 and nine years later (Galton, 1892). He reported that the minutiae patterns persisted and grew together with the digit despite the changing dimensions (length and breadth) of the pattern (Galton, 1892). Despite the permanence of the minutiae pattern, the study of Haraksim *et al.* (2019) showed that the growing friction ridge skin of juvenile individuals goes through a ‘biometric displacement’ of the pattern which can pose a challenge for fingerprint recognition technology in cases where

juvenile fingerprints are compared to their counterparts collected after longer time periods.

In adult individuals, Chacko and Vaidya (1968) described ageing of the friction ridge skin as a flattening of epidermal ridges and loss of elasticity in the dermis. According to Tobin (2017), the recovery response after mechanical depression in young individuals lasts only minutes whereas in the elderly this can take up to 24 hours. The loss of elasticity is demonstrated in the wrinkled and flaccid appearance of friction ridge skin in older individuals.

The epidermal ridges flatten due to an atrophic epidermis and remodelling in dermal papillae (Chacko and Vaidya, 1968). According to their study, Chacko and Vaidya (1968) show that remodelling is life-long and varies locally depending on the shearing stresses that are applied to a particular area of friction ridge skin. Epidermal anastomoses, sheets of connective tissue formed by the epidermal basal layer which connect it to the top surface of dermal papillae, cause the papillary surface to divide into more complex structures with increasing shear forces (Maceo, 2011). As attachment between the papillae and epidermal anastomoses experience greater strain, the dermal papillae develop into more complex undulating shapes, increasing the surface area of attachment between epidermis and dermis and so enforcing the bond between these two layers (Chacko and Vaidya, 1968). Therefore, with increasing age, the dermal papillae change their morphology (Hale, 1952; Chacko and Vaidya, 1968; Okajima, 1979; Misumi and Akiyoshi, 1984).

In a foetus, there are double rows of papillae underlying each epidermal ridge; in adults, the number of the papillae tends to increase with age and they also become denser (Okajima, 1979; Misumi and Akiyoshi, 1984). Although the double-row arrangement in dermal papillae is retained, Okajima (1979) reports new dermal papillae forming occasionally throughout life, even under the existing epidermal furrow. Papillae developing under the epidermal furrows may influence the floor of the furrows. According to Okajima (1979), however, this change does not influence the configuration of epidermal dermatoglyphic characteristics. Lavker (1979) and Kücken (2007) also claim that increased branching of dermal papillae with increasing age does not affect the surface ridge and furrow

characteristics since dividing and specialising keratinocytes are protected from changes in the dermis by a basal lamina and retain their division in a non-disturbed manner. Misumi and Akiyoshi (1984) in contrast claim that proliferation and multiplication of dermal papillae with increasing age can cause possible changes in minutiae types and overall loss of ‘dermal surface localisation’, which makes a comparison of the epidermal and dermal skin layer in elderly individuals challenging. Furthermore, a study by Stücker *et al*. (2001) indirectly supports the proliferation of dermal papillae which affects the appearance of epidermal layer friction ridges. In a sample of 121 German individuals, they studied the frequency of interpapillary lines, also known as interstitial ridges (thin epidermal ridges located within epidermal furrows) (Figure 2.3.1) and found an increased occurrence of this feature with increasing age of individuals.

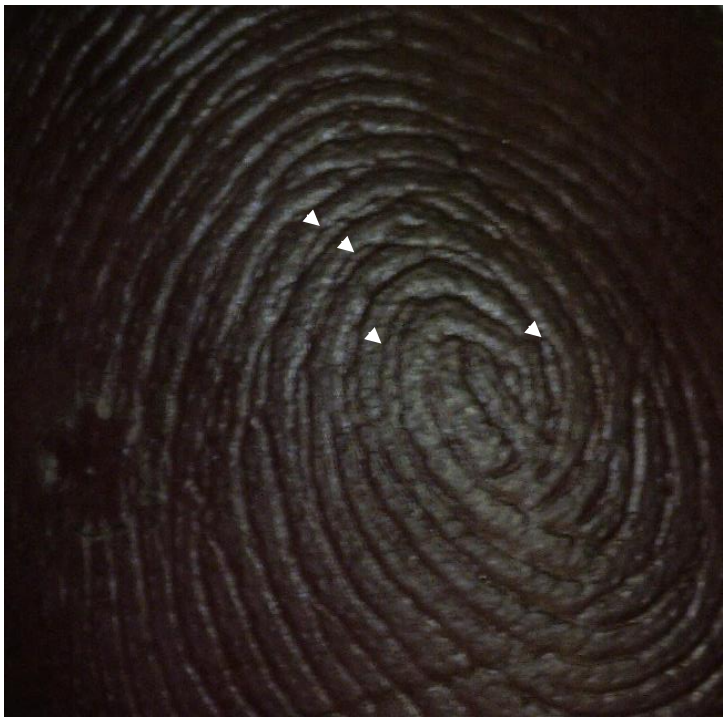

Figure 2.3.1 Photograph of a fingertip showing examples of interstitial ridges (white arrowheads).

There is evidence of a decrease in the thickness of the epidermis with increasing age; the proliferation of basal keratinocytes decreases by 30-50% between the age of 30 and 80 years (Petersen, 2001; Maceo, 2011). According to Lavker *et al*. (1987), general flattening of dermal papillae occurs with increasing age, which causes flattening of epidermal ridges. This, together with previously mentioned epidermal thinning, can contribute to a decreasing quality of fingerprints. In the

study of Bossen *et al.* (2010) they imaged dermal and epidermal layers with optical coherence tomography and found differences between different age groups such that the friction ridge skin of people between 20 and 30 years of age shows better-defined images than the friction ridge skin of people aged over 40. Bossen *et al*. (2010) concluded that older people possess a less pronounced dermal papillary layer than younger age groups. Although the frequency and position of epidermal ridges and furrows are not affected by the aging process according to Bossen *et al.* (2010), flattening of the ridges affects the quality of fingerprints and as a result it may become difficult to follow the ridge flow and some minutiae characteristics may be obscured. Moreover, Nagesh *et al.* (2011) found the characteristics (type, size, shape, position) of sweat pores on epidermal ridges also changed with increasing age.

Further age-related changes to the friction skin ridge are connected to the formation of wrinkles. Skin becomes more fragile, as the dermis becomes less dense and decreases its microvasculature (Montagna and Carlisle, 1979; Petersen, 2001). According to Lavker *et al.* (1987), collagen bundles start to unravel and elastin loses its elasticity, slowly disintegrating which in turn results in sagging of the skin and fine wrinkling. Although the age-related changes occur in friction ridge skin over decades, they may result in obscured minutiae characteristics and lessening of identification potential of given fingerprints, especially in cases of partial prints (Maceo, 2011). The loss of information in dermal fingerprints from elderly individuals could have a negative impact on fingerprint comparison where ante-mortem fingerprints were collected years before, such as in cases of missing persons or a localised disaster victim identification incident where ante-mortem data is lost in the event as well.

2.3.2 Genetic disorders and other medical conditions

Due to the genetic component in the development of the friction ridge skin, there is the possibility that abnormal ridge patterns can develop in various cases of genetic mutation (all supporting citations can be found in Table 2.3.1 which contains a summary of genetic disorders involved in alteration of friction ridge skin). Four main types of genetic malformations of friction ridge skin have been reported: adermatoglyphia/ridge aplasia (absence of epidermal ridges), ridge hypoplasia (ridges of reduced height), ridge dissociation (ridge segment into dot-

like patterns), ridges-off-the-end (ridges flowing vertically from the top of the fingertips); a fifth type was also observed – a combination of the last two types (David, 1973; Schaumann and Alter, 1976; Burger *et al.*, 2011). According to David (1973), caution needs to be applied when assessing ridge dissociation. He reports it can be mistaken for scarring, post-burning injuries healed as granulations and *vice versa*. Moreover, Penrose (1967) also proved there is a relationship between the number of sex chromosomes and ridge count and breadth. With increasing numbers of sex chromosomes, there is an increase in breadth of the friction skin ridges and a decrease in their number (Penrose and Loesch, 1969). This was also proved by Hall and Gilchrist (1990) and Lowenstein *et al.* (2004) who described individuals with Turner syndrome (XO chromosomal aneuploidy) as having a greater ridge count when compared to XX and XY individuals. In a similar way, patients with Klinefelter's syndrome tended to have decreased total finger ridge count with increasing number of X or Y chromosomes, as suggested by Shiono *et al.* (1977). Developmental alterations of fingerprint ridge characteristics *in utero* can be also be caused by medical interventions, as in the case of anticonvulsant drugs which when taken by the mother, affect the appearance and frequencies of certain fingerprint patterns (Bokhari *et al.*, 2002).

Friction ridge skin can also be subject to disorders affecting the structure of epidermal and dermal skin layer. Table 2.3.2 contains a summary of skin conditions altering friction ridge skin. These conditions affect either the junction between the epidermis and dermis or impact cells in one or other of the skin layers. In such cases, the appearance of friction ridge skin may be altered temporarily or permanently.

Whether it is due to genetic or other types of medical skin conditions, the mentioned abnormalities can hamper identification using friction ridge skin, especially in cases of automated fingerprint recognition systems (Drahanský *et al.*, 2009; Drahansky *et al.*, 2012; Drahanský and Kanich, 2019). On the other hand, specific pattern arrangement connected to a genetic condition or the presence of scars can provide valuable individualising characteristics and aid in the identification process (Schaumann and Alter, 1976). Moreover, in cases of some of the most prevalent skin conditions, such as acrodermatitis, psoriasis,

and warts, specific algorithms were developed to help with the challenging task of electronic capturing and automated identification of the friction ridge skin with such conditions (Drahanský and Kanich, 2019).

Table 2.3.1 Summary of genetic disorders involved in alteration of friction ridge skin.

Abnormality	Associated disorder	Cause	References
ridge aplasia or adermato-glyphia	carcinomas	chemotherapy	Haber *et al.* (2015)
	isolated feature, reduced ability of hand transpiration	genetic	Baird (1964, 1968); Burger *et al*. (2011); Nousbeck *et al*. (2011)
	Basan syndrome	genetic	Basan (1965)
	blisters, fissuring, contracture of digits	genetic	Reed and Schreiner (1983); Límová *et al*. (1993)
ridge aplasia as minor feature	Kindler syndrome	genetic	Wiebe and Larjava (1999); Binder *et al.* (2002)
	Naegeli-Franceschetti-Jadassohn syndrome	genetic	Itin *et al.* (1993); Lugassy *et al.* (2006)
	dermatopathia pigmentosa reticularis	genetic	Heimer *et al.* (1992); Brar *et al.* (2007)
	dyskeratosis congenita	genetic	Sirinavin and Trowbridge (1975)
ridge pachydermia	keratitis-ichthyosis-deafness (KID) syndrome	genetic	Grob *et al.* (1987); Caceres-Rios *et al.* (1996)
	Clouston syndrome	genetic	Jan *et al.* (2004)
ridge hypoplasia	Christ-Siemens-Touraine syndrome	genetic	Rodewald and Zahn-Messow (1982); O'Donnell and James (1992)
	Rapp-Hodgkin ectodermal dysplasia	genetic	Rodewald and Zahn-Messow (1982); O'Donnell and James (1992); Atasu *et al.* (1999)
	coeliac disease (acquired)	genetic predisposition, autoimmune inflammatory disorder	David (1973)
ridge dissociation	de Lange syndrome	genetic	David (1973)
	Down syndrome	genetic	David (1973); Schaumann and Alter (1976)
	trisomy-18/normal mosaic	genetic	David (1973); Schaumann and Alter (1976)
	D1 trisomy	genetic	David, (1973)
	cystic fibrosis (reversible)	unknown	David, (1973)
	intestinal pseudo-obstruction (reversible)	unknown	David, (1973)
parallel ridge pattern	acral melanoma	genetic	Blázquez *et al.* (2009)

Table 2.3.2 Summary of disorders affecting the structure of the epidermal and dermal skin layer.

Disturbance of ridge skin	Associated disorder	Cause	Reference
excessive epidermal desquamation	eczema on finger/palm surfaces	changes on the junction between dermis and epidermis	Pour-Jafari *et al.* (2003)
water-filled vesicles in friction ridge skin	pompholyx (dyshidrotic eczema)	idiopathic reaction	Drahanský *et al.* (2009); Drahansky *et al.* (2012)
blistering of fingertips	pyoderma	bacterial infection	Wolff *et al.* (2005)
punch-like depressions in the skin surface	pitted keratolysis	bacterial infection	Kaptanoglu *et al.* (2012)
skin ulcers and lesions	*lichen planus*	unknown aetiology	Madke *et al.* (2013)
hypertrophy of dermal papillae, brown thickening of skin, complete distortion of epidermal pattern	*acanthosis nigricans* (obesity, diabetes, tumours)	nonspecific reaction	Farrant and McGibbon (2004); Verbov (2005)
vascular lesions, epidermal crusting	pyogenic granuloma	injury, hormonal response, human papilloma virus, Orf virus	Wollina *et al*. (2017)
fingertip necrosis	systemic sclerosis	autoimmune disease	Young *et al.* (2016)
necrosis of appendicular tissues	leprosy	bacterial infection	Vera-Cabrera *et al.* (2011)
lesions, blisters formation	herpes simplex virus infection (associated with HIV)	herpes simplex virus	Tschachler *et al.* (1996)
vesicles and crust formation	scabies	mite disease	Haber *et al.* (2015)
lesions with blisters, haemorrhages, necrosis, crusting	*erythema multiforme* (associated with herpes virus)	herpes virus	Stampien and Schwartz (1992)
lesions, other self-inflicted skin injuries	*dermatitis artifacta* (associated with psychosis, drug abuse)	patient manipulation	Wojewoda *et al.* (2012)
epidermal desquamation	scarlet fever	bacterial infection	Curran and Al-Salihi (1980); Stevens *et al.* (1989)
epidermal desquamation	Kawasaki's disease	unknown	Gupta and Singh (2016)
lesions, scaling skin eruptions	syphilis (secondary)	bacterial infection	Baughn and Musher (2005)
hyperplasia, hyperkeratinosis, scarring	warts	human papilloma viruses	Bristow and Greenwood (2009)
plaques formation, scaling	psoriasis	genetic	Jilek (1972); Pour-Jafari *et al.* (2003)
minor trauma causes non-inflammatory blistering, scarring	*epidermolysis bullosa*	genetic	Sprecher (2010)
dermatoses: e.g. lichenosis	drug-induced skin reactions	sulphonamides, anticonvulsants	Ahronowitz and Fox (2014)

2.3.3 Intentional and accidental (occupational) changes

There are multiple historical and current sources reporting intentional fingerprint alterations as means of preventing identification usually in criminals and asylum seekers (Cummins, 1935; Yoon *et al.*, 2012; U. S. Federal Bureau of Investigation, 2015; Haraksim *et al.*, 2016). The main types of fingerprint alteration are obliteration (burning, acid/base mutilation, abrasion, stitching, and transplantation of skin with no ridge detail present), imitation (surgical swapping of skin between the digits or hands/feet), and distortion (vertical cuts, Z-shaped cuts through the digit pad) – these are permanent changes to the skin layers (Yoon *et al.*, 2012; U. S. Federal Bureau of Investigation, 2015; Haraksim *et al.*, 2016). Yoon *et al.* (2012) stress the importance of distinguishing between permanent alteration of fingertips performed when an individual desires to mask their identity and the use of fake fingerprints, which are only temporary and are typically used to adopt someone else's identity. Whereas fake fingerprints are reportedly recognised via liveness detection (detecting blood pressure in live digits and or skin distortion of fingerprints made by live digits) by some fingerprint scanners, altered fingerprints still present a challenge in automated fingerprint recognition systems (Yoon *et al.*, 2012; Haraksim *et al.*, 2016).

Occupational alteration of fingerprints (loss of depth and flattening of ridges, scarring) is often anecdotally connected to individuals who work manually in construction sites. Drahansky *et al.* (2012) also mention eczema occurring in construction and cement workers which can lead to permanent alteration of their fingerprints. According to Maceo (2011), there are also temporary morphological features that appear on the friction ridge skin and are associated with various occupations; these may be warts, wrinkles, blisters, cuts or calluses. All of the alterations mentioned above will cause difficulties with regards to electronic recognition of fingerprints (Maltoni *et al.*, 2009; Yoon *et al.*, 2012; Haraksim *et al.*, 2016). However, depending on the extent of the damage done to the ridge details, identification may still be successful in some cases when fingerprints are collected by more traditional means (ink, powder) (Cummins, 1935; Yoon *et al.*, 2012).

2.3.4 Post-mortem changes

After death the human body undergoes changes; the sequence, magnitude, and period over which these changes occur depend on environmental factors, the parameters of the body itself and the circumstances of death (Gahr *et al.*, 2013; Czubak *et al.*, 2015; Caruso, 2016). The post-mortem and circumstantial changes potentially altering the appearance of friction ridge skin are wrinkling as a result of immersion ("washerwoman's hands"), skin desquamation, advanced putrefaction, mummification, saponification (adipocere formation), trauma, and carbonization (Ferguson, 1966; Reh, 1984; Kahana *et al.*, 2001; Cattaneo *et al.*, 2006; Mulawka, 2014; Czubak *et al.*, 2015; Caruso, 2016; Armstrong and Erskine, 2018). Putrefaction can cause either epidermal desquamation or in more advanced cases, complete degradation of the epidermis and friction ridge details (Cattaneo *et al.*, 2006). In cases where ridge detail information is lost in the epidermal layer, the dermal layer can be employed for identification purposes, providing decomposition does not cause a concomitant loss of papillary design (Ferguson, 1966; Okajima, 1979, 1984; Mizokami *et al.*, 2015). Mummification is a result of extreme dehydration and is responsible for hardening and pronounced folding of the skin (Fields and Molina, 2008). In cases of saponification, the skin may show signs of flaking and flattening of dermal papillae; the ridge detail may be obscured by adipocere formation (Cattaneo *et al.*, 2006). Alteration of ridge detail characteristics due to carbonization is often demonstrated as dehydration of the epidermis and connected wrinkling, loss of skin layers, and thinning alterations to dermal papillae (Cattaneo *et al.*, 2006; Porta *et al.*, 2007). In all cases mentioned above, the state of the altered ridge detail and techniques used to collect the fingerprint information will dictate the success of identification (Kahana *et al.*, 2001; Czubak *et al.*, 2015; Morgan *et al.*, 2018). Collection techniques used for fingerprint collection from deceased individuals in various conditions are described further in section 2.5.1.1.

2.4 Fingerprints as identifiers

2.4.1 Principles of friction ridge skin comparison

Fingerprints are considered to be a biometric identifier (Jain *et al.*, 2000). Biometric identifiers are defined as distinguishing physiological and/or behavioural characteristic that according to Jain *et al.* (2000) should ideally be universal (possessed by each person), collectable (readily presentable), permanent (unchanging over time), and unique (each person possesses a different version of it). However, even Jain *et al.* (2000) admits that in practice biometric characteristics that fulfil all requirements might not be feasible. In case of fingerprints, it was proven by multiple studies mentioned in section 2.3 that although friction ridge skin ridge flow and minutiae characteristic remain in place throughout an individual's life, their quality and distinguishability is alterable due to pathologies, advanced age, occupation, and/or accidental/intentional damage (Chacko and Vaidya, 1968; Misumi and Akiyoshi, 1984; Stücker *et al.*, 2001; Drahanský *et al.*, 2009; Yoon *et al.*, 2012). Furthermore, multiple studies proved that the concept of uniqueness is an assumption and needs to be replaced by a more defensible empirical concept with probabilistic foundation not only in the case of fingerprint comparison but in numerous other fields of forensic science (Saks and Koehler, 2005; Neumann *et al.*, 2007; Cole, 2009).

To understand the underlying principles of the matching process, it is essential to briefly describe the basic classification of the patterns that are used in the analysis of friction ridge skin. Although the same principles apply when examining and comparing fingerprints and finger marks, these two terms are used for different representations of friction ridge skin impressions. To clarify the terminology, a finger mark is an impression of friction ridge detail left as a result of the uncontrolled contact from the digits of the hand with a substrate (Forensic Science Regulator, 2017c). Sometimes the marks may not be readily visible on the substrate and in such cases, they are called latent marks and require the use of visualisation techniques before collection or analysis (Forensic Science Regulator, 2017c). In contrast, a fingerprint is an impression of friction ridge detail from digits of a known source (Forensic Science Regulator, 2017c).

Friction ridge skin morphologic characteristics bear the potential for identification of individuals (Faulds, 1880; Herschel, 1880). The foetal development and

underlying anatomy of friction ridge skin give rise to friction ridge skin characteristics which differ even between monozygotic twins (Jain *et al.*, 2002). Fingerprint experts and various software algorithms who/which utilise the characteristics in the identification process distinguish three levels of detail in friction ridge skin morphology, these are simply referred to as first, second, and third level details (Ashbaugh, 1999; Hutchins, 2011).

First level details refer to the flow of ridges and the type of ridge pattern. Flow of the ridges can be found on the palmar/plantar side of the digits as well as on the palm of the hand and plantar side of the foot at the sites which used to be volar pads, structures present during intrauterine development, for more information see section 2.2.2 (Champod *et al.*, 2016). Patterns refer to the arrangements of skin friction ridges and usually contain a core centre to the pattern (located at the approximate centre of a friction ridge pattern) and may contain delta/s (a triangular-shaped place where ridges with different flow directions meet) (Figure 2.4.1) (Galton, 1892; Ashbaugh, 1999). Throughout the history of fingerprint identification, there have been multiple classifications of core patterns, but three main types (arch, loop, whorl) are a reoccurring theme with each of their deviations either being classified as a separate category or sub-classified under one of the main three (Figure 2.4.2) (Galton, 1892; Ashbaugh, 1999; Hutchins, 2011; Grzybowski and Pietrzak, 2015). Currently in the UK, there are several subcategories of the three main patterns. For arch core patterns, this includes approximating, plain, and tented arch. For loop core patterns, this includes central or lateral pocket (loop), nutant or twinned loop, and radial or ulnar loop. For core patterns this includes whorl and elongated whorl. There are also patterns either non-conforming to any of the groups called accidentals (has two or more deltas) or being composed of more patterns called composite (has three or more deltas) (Figure 2.4.2) (Forensic Science Regulator, 2017c). Some fingerprint patterns are more frequent than the others, but matching fingerprints based only on this level of detail does not possess sufficient discriminating power for identification (Gutiérrez *et al.*, 2007).

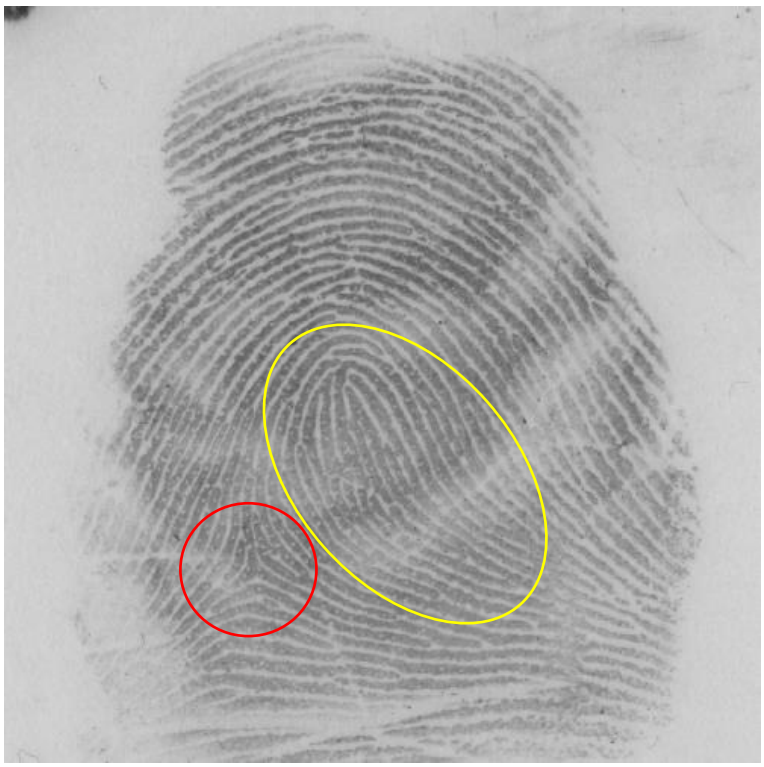

Figure 2.4.1 Example of a core pattern (yellow ellipse) and delta (red circle).

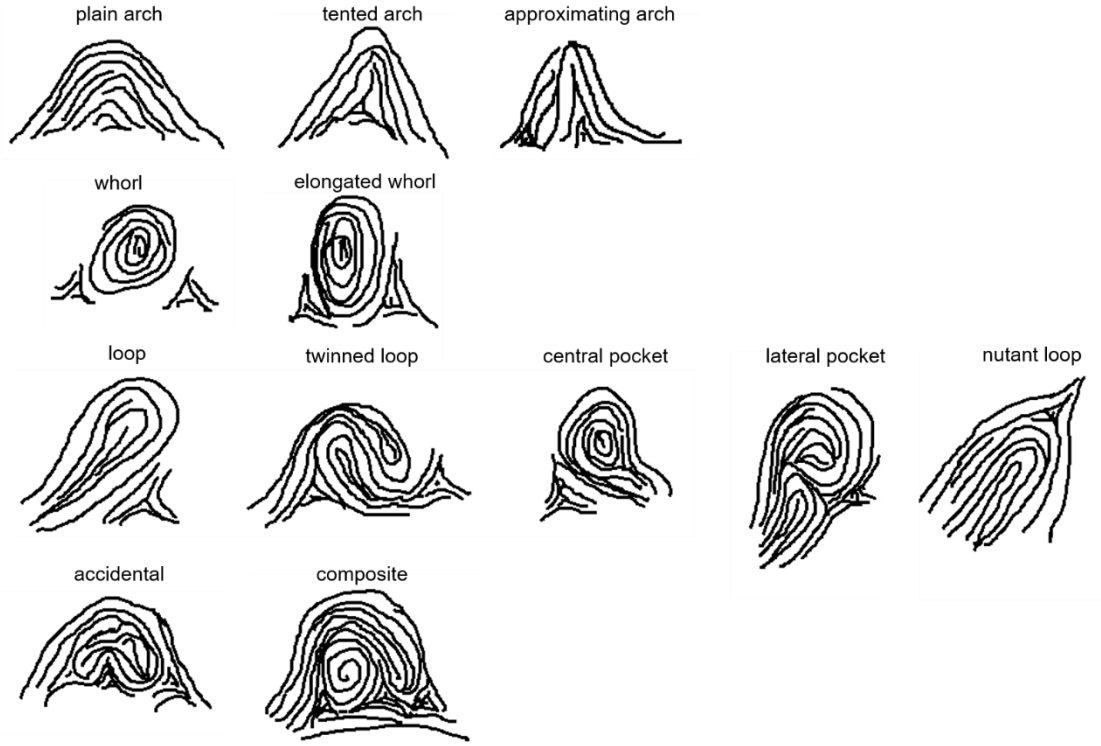

Figure 2.4.2 Schematics of fingerprint core patterns.

Since first level patterns do not differentiate sufficiently for the purposes of identification, the experts dive deeper and compare second level details of the

friction ridge skin (Vanderkolk, 2011). Second level details are sometimes called minutiae or minutiae characteristics, as they describe small details or ‘events’ along the friction ridge path (Galton, 1892). According to Ashbaugh (1999), the most frequent characteristics are ridge ending, and bifurcation/convergence, however, there are more types of friction ridge characteristics. The guidelines of the Forensic Science Regulator (2017) mentions six basic friction ridge characteristics minutiae: ridge ending, bifurcation, short independent ridge, lake, crossover, and spur (Figure 2.4.3). More examples of minutiae (14 types) can be found described by Gutiérrez *et al.* (2007). The second level friction ridge characteristics may also include scars, wrinkles, creases, and warts when found on both compared friction ridge skin items (Campbell, 2011).

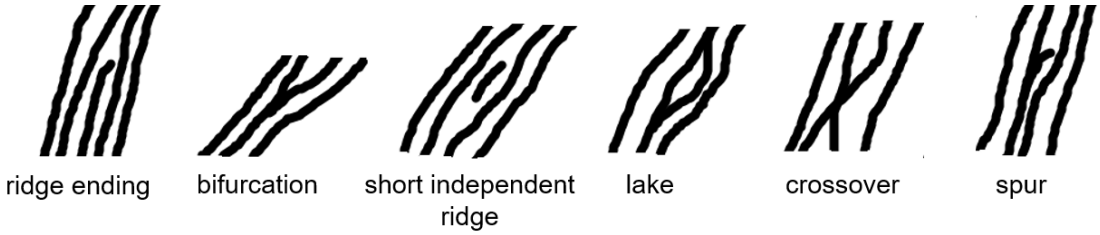

Figure 2.4.3 Schematic of basic friction ridge minutiae second level details drawn according to the descriptions in the Forensic Science Regulator (2017).

Third level friction ridge details include the shape of friction ridges, detail of the ridge edges, their width and texture, as well as the relative location of sweat pores (Vanderkolk, 2011). If the quality of the fingerprint allows for sufficient investigation, pores are studied for their size, shape, and arrangement within the friction ridge skin (Forensic Science Regulator, 2017c). It is important to note that with increasing level of details there is also an increased possibility of feature alteration when fingerprints are collected (Bindra *et al.*, 2013). Analysis of third level details is therefore highly dependent on the quality of the print/mark. Moreover, the appearance of sweat pores and dimensions of ridges are influenced by the amount of pressure applied when a fingerprint is deposited (Bindra *et al.*, 2013). This poses certain challenges, and a note of warning is needed when the identification of individuals is based on the comparison of third level details.

Depending on the quality of the fingerprints, fingerprint experts will employ suitable levels of friction ridge detail in the comparison process (Ulery *et al.*,

2013). Fingerprint experts visually examine and compare friction ridge skin impressions from an unknown source with reference friction ridge skin impressions from a known source (Campbell, 2011). To illustrate, finger marks recovered from a crime scene would be compared to reference fingerprints of known individuals. Fingerprints recovered from an unidentified deceased individual would be compared to finger marks recovered from a place of work or home of the person that it is suspected to be. More details about the specifics of comparison and matching processes can be found in section 2.5.2.

2.4.2 History of fingerprint use for identification purposes

Several sources offer chronological overviews of friction ridge skin impression utilisation in the human identification process (Caplan, 1990; Berry and Stoney, 2001; Cole, 2004; Champod and Chamberlain, 2009; Barnes, 2011; Campbell, 2011). A summary will be presented here. It is important to underline the difficulty of distinguishing facts from speculations and/or subjective opinions included in the historical literature dedicated to this topic. Unsurprisingly, the closer in the timeline of fingerprinting history we are to the current day, the more accurate and objective the record becomes, but a measure of patriotism and subjective preferences can still be detected even in some of the more current sources. It is also important to distinguish between three various perspectives on the ‘history of fingerprints’:

- the process of biological evolution of friction ridge skin characteristics,
- the history of people becoming aware of their friction skin ridges, such as supposed artists depicting friction ridges described by Berry (1976) and Berry and Stoney (2001), or biologists describing friction ridges as a mere skin feature (Grew, 1684; Malpighi, 1686; Cummins and Wright Kennedy, 1940),
- the history of the use of fingerprints for authentication and identification purposes.

This section will concentrate on the third part of the topic, although it needs to be acknowledged that without the first two no discussion about the last would be possible.

The earliest theory about the use of fingerprints as supposed authenticators was reported from China (Xiang-Xin and Chun-Ge, 1988). People imprinted their finger into a clay seal to secure documents against unauthorised opening. These clay seals are dated back to between 221 before Christ (B.C.) and 220 *anno Domini* (A.D.). However, the paper of Xiang-Xin and Chun-Ge (1988) does not provide any evidence for these fingerprints actually being used as authenticators of the people sealing the document and there is a possibility for such fingerprints being simply a security seal. Xiang-Xin and Chun-Ge (1988) document the early use of hand and digit impressions for authenticating legal documents in China. Phalangeal creases of palmar hand impressions (and distance between the creases) have been used in legal documents along with a person's signature as an authenticator for authorities since the 6th century. The authors do not give any proof of fingerprints themselves being used in legal document authentication before the 14th century. The same authors also claim that the first time handprint comparison was used in a criminal investigation of fraud in the 10th century was also in China (Xiang-Xin and Chun-Ge, 1988). However, there was no mention of fingerprint characteristics being employed in the identification, only that hand impressions on two compared documents were deemed to be made by the same individual and that one was made on a blank piece of paper and then writing was added at a later date proving the document as fraudulent.

As was pointed out by Cole (2004), selecting the correct identity from a pool of possible candidates (identification) is a slightly different concept to verification of an individual's identity claim (authentication). Suggestions for the use of fingerprints for identification purposes were first published by a United States of America (USA) national, a specialist in microscopy, Thomas Taylor, in 1877 (Taylor, 1877; Dillon, 1972 both as referenced by Cole, 2004[1]). Thomas Taylor proposed the use of fingerprints (finger marks) deposited in blood and left at a crime scene to identify a suggested perpetrator. Around the same time, another scientist published his observations and suggestions for the use of fingerprints in the field of identification. Scottish physician Henry Faulds undertook this whilst working in Japan (Faulds, 1880). Faulds' publication received what could be described as a polite but somewhat passive-aggressive reaction from William

[1] Unable to source the primary sources due to lockdown caused by COVID-19 pandemic.

Herschel, who was an English colonial administrator in India (Herschel, 1880; Cole, 2004). Herschel was inspired by the Bengali practice of signing documents by inked fingerprints and claimed he suggested using fingerprints as identifiers for arrested criminals in his letter to a Bengali jail inspector in 1877, before Faulds' publication in Nature, thus beating Fauld's claim of being the first in suggesting fingerprints for identification (Herschel, 1880; Berry and Leadbetter, 1987). Apparently, neither Faulds nor Herschel knew about the publication of Taylor, and the two continued to dispute each other's claim of precedence for a further 50 years (Cole, 2004). According to Berry and Stoney (2001), Herschel also undertook research into the permanence of friction ridge skin and is the first person to document relative ridge persistency based on a collection of his palm prints taken over decades. Although Herschel claimed extensive experience in fingerprint collection and research (over 20 years before writing the letter to the jail inspector), unlike Taylor and Faulds he did not connect fingerprint (finger mark) identification to possible crime scene scenarios (Berry and Leadbetter, 1987; Cole, 2004).

The utilisation of fingerprints in identification, especially in the area of criminal law, became more of a possibility when it was proven it can be a more effective and 'user-friendly' solution than anthropometry, which had been in use since Alphonse Bertillon developed and implemented the approach in France in 1882 (Caplan, 1990). In anthropometry, a set of eleven precise anthropometric measurements were taken from arrested people by trained specialists to ensure each arrestee could be identified. Proving that fingerprints were more efficient than anthropometry was a deed achieved by separate contributions from multiple scientists. Among the most known is Francis Galton, an English anthropologist who described minutiae ridge details and suggested the detailed use of fingerprints in identification (Galton, 1892). His work was scrutinised by the British Home Office, which adopted taking fingerprints alongside anthropometry as a means for identification in 1893 (Berry and Stoney, 2001). It is important to note that Galton was inspired in his observations and classification of fingerprint patterns by the work of Bohemian physiologist Johannes Evangelista Purkinje (also Jan Evangelista Purkyně/Purkynje/Purkenje in some literature sources) (Grzybowski and Pietrzak, 2015). Purkinje did not suggest fingerprints as identifiers but was the first person who classified fingerprint ridge patterns into 9

classes and published this classification in 1823 (Purkynje, 1823; Galton, 1892; Cummins and Wright Kennedy, 1940, 1987; Grzybowski and Pietrzak, 2015).

Before Galton's suggested system of fingerprint-based identification fully replaced Bertillon's anthropometric protocol, the indexing system for collected fingerprints was devised by two separate groups of scientists. One was Argentinian fingerprint expert Juan (Ivan) Vucetich who developed an indexing system in 1893 using the combinations of ten-finger pattern types plus ridge counting within the core pattern of fingerprints (Berry and Stoney, 2001; Cole, 2004; Barnes, 2011). His system of fingerprint identification and cataloguing was employed by the Argentinian police instead of Bertillon's cumbersome anthropometric identification in 1896 (Barnes, 2011). Vucetich is also described as the first expert who assisted with solving a homicide case solely by utilising fingerprint-finger mark comparison to provide a resulting identification in 1892 (Cole, 2004). The second group of scientists were based around Edward Henry, an English inspector general working in India, who together with police officers Azizul Haque and Hem Chandra Bose developed a classification method of fingerprints in 1895; the method was very similar to Vucetich's classification system, again based on fingerprint pattern types (International Biometric Group, 2003; Cole, 2004; Sodhi and Kaur, 2005). As a result of the work of Henry, Haque, and Bose, fingerprints replaced Bertillon's anthropometry in identification within the British legal system in 1900 (Cole, 2004). Other countries around the world took various approaches to replacing Bertillon's anthropometric approach of identification with fingerprints, some countries transitioned completely to fingerprints, some used a hybrid method utilising both techniques, while some used anthropometry for serious offenders in prisons and employed fingerprints in the military and for petty criminals (Hutchins, 2011). However, a transition to fingerprints as sole identifiers eventually occurred in most countries between 1890 and 1930. All of these countries utilised either the classification system of Henry or Vucetich or a derivate of both methods (Cole, 2004). With time, countries have slightly adapted and adjusted the fingerprint classification and identification methods (Hutchins, 2011).

Since Galton's description of ridge minutiae characteristics, fingerprint comparison and matching were based on the appearance and relative location of

these minutiae (Galton, 1892; Caplan, 1990). In 1914, Edmond Locard first attempted to estimate a minimum number of minutiae that must match for an identification to be established, he estimated that this should be 12 points in a sharp clear print (Cole, 2004). Some countries still adhere to a numerical threshold today, whereas other countries, the UK included, abandoned the numerical approach in the favour of a holistic approach (both approaches are discussed in more details in section 2.5.2) (Leadbetter, 2005; Campbell, 2011; Adam, 2016).

As increasing numbers of fingerprints were recorded and catalogued, a need for an automated fingerprint pattern recognition system was recognised. Using Henry's classification system, it was obvious that with the increasing number of recorded fingerprints, the power of distinction between the individuals recorded in the system decreased and more detailed fingerprint core pattern subclasses would need to be developed (Hutchins, 2011). Moreover, it was difficult and time-consuming to manually search the database of fingerprint ink cards for possible previously unidentified suspect candidates to compare against a finger mark from a crime scene (Cole, 2004). Furthermore, Cole (2004) also mentions that searching Henry's system with a finger mark from a crime scene which did not have a preserved core pattern did not help with identification. The answer to these problems came in the late 20th century, as the prototype of an automated fingerprint pattern recognition system was developed in 1972 in the USA (Cole, 2004; Moses *et al.*, 2011). As they developed, the automated systems stored relational data between minutiae of a single fingerprint/finger mark, making the search of the database faster and more effective, although final matching still depends on the work of fingerprint experts (Homeland Security Technologies, 2005; Moses *et al.*, 2011).

2.4.3 Current biometric uses of friction ridge skin

Friction ridge skin continues to be used for identification purposes in the criminal justice system and apart from identification of the living, it is also utilised as one of the primary identifiers in cases of unidentified bodies (Morgan *et al.*, 2006; Ferreira *et al.*, 2011; Turner, 2013). However, with the fast development of various automatic recognition technologies, the use of fingerprints as identifiers has expanded outside of criminal or disaster boundaries, and biometric systems

based on recognition of fingerprints have become extremely successful in civilian applications (Maltoni *et al.*, 2009). Fingerprint recognition systems are used to monitor the attendance of employees, students, even patients within the health care system (Dalah, 2014; Patni and Sharma, 2017; Datt *et al.*, 2018). With the increasing use of fingerprint recognition systems for such purposes, the protection of digital data has been introduced into wider personal data legislation. Vojković and Milenković (2018) offer a useful summary of how the impact of the General Data Protection Regulation (GDPR) passed by the European Parliament affects the users of such systems (European Parliament and the Council, 2016). Aside from attendance control, fingerprint recognition systems are a part of electronic devices, such as laptops or mobile phones as one of the options for secured access control (Hattersley, 2013; Hassan and Kim, 2018). Fingerprint access points/locks are used in security systems for authorisation of access to various facilities and private premises (Kim *et al.*, 2008). Moreover, companies developing fingerprint recognition systems are currently promoting the use of fingerprint verification in banking; smartphone fingerprint verification is combined with various smart cards, universal serial bus (USB) tokens, and watches (Fingerprints, 2019).

All the relevant software and hardware facets of fingerprint recognition systems are rapidly evolving to provide users with spoof-proof products, which are resilient to environmental conditions and the preservation state of friction ridges and/or individuals (Guillen *et al.*, 2012; Johnson and Riemen, 2019). The level of security and sensitivity of each system depends upon the types of sensors that are used to ‘read’ the friction ridge skin (Triggs, 2019). Optical scanners are more sensitive to the quality/cleanliness of the friction ridge surface allowing them to capture an image of sufficient quality for comparison purposes; these are however more prone to being spoofed when using soft synthetic casts of friction ridge skin (Liu *et al.*, 2000). There are also capacitive sensors utilising the electrical conductivity of living humans and sensors utilising the thermal signature of blood flowing in dermal papillary capillaries; these are useful to track ‘liveness’ of the subject, however, their performance can be impacted by the environmental temperature, the level of vascularisation of individuals’ digits, and clean ‘noiseless’ friction ridge surfaces (capacitive sensor) (Han and Koshimoto, 2008; Hassan and Kim, 2018). More recently, sensors have been developed that utilise ultrasonography or

optical coherence tomography. These claim to be able to penetrate the surface and capture friction ridge detail that is present on the sublevels of the skin (Schneider, 2008; Lamberti *et al.*, 2011; Costa *et al.*, 2016; Jiang *et al.*, 2017). Some sensor developers claim to utilise dermal layer friction ridge skin in such scanners, providing the solution to spoofing and any superficial damage/debris deposits which might be present and might obscure the surface of friction ridge skin (Schneider, 2008; Costa *et al.*, 2016). However, as Auksorius and Boccara (2017) rightly pointed out, it is a sub-layer of the epidermis, rather than dermis which is being utilised in sensors that claim to capture the dermis. Despite the ambiguity of the visualised skin sub-layer, such sensors appear a promising solution for not only reducing spoofing but also for fingerprinting of deceased individuals (Johnson and Riemen, 2019).

2.5 Friction ridge skin impression as forensic evidence

As mentioned in the previous chapter, friction ridge skin has been employed as a means to identify individuals in the UK criminal justice system since 1900 (Berry and Stoney, 2001; Hutchins, 2011). This section introduces the main steps currently involved in the identification process based on the comparison of friction ridge skin details in the UK, namely fingerprint collection, its analysis, comparison, evaluation, and verification. The main problems of identification based on friction ridge skin detail comparison in the forensic setting are also mentioned.

2.5.1 Collection

The difference between a fingerprint and a finger mark also means using different approaches when collecting and processing them. Fingerprints, being taken from living or deceased individuals under controlled conditions, do not tend to undergo any post-processing regarding visualisation as is the case with latent finger marks. There is a wide variety of techniques for the visualisation, lifting, and imaging of latent finger marks which assist with collecting the maximum amount of information available from the impression. The techniques include powder and liquid media, different wavelength light sources, fuming, metal particle deposition, and their combinations (Sears *et al.*, 2012; Bleay *et al.*, 2017). The techniques vary as they need to be applied to finger marks of various, often unknown, composition (sweat, protein, blood, drug, food particles) (International Fingerprint

Research Group, 2014). Moreover, the finger marks are deposited on substrates with multiple variable properties (structure, colour, porosity), creating numerous challenges for visualisation, lifting, and imaging (International Fingerprint Research Group, 2014). Although in DVI situations the latent finger marks tend to be of interest when collecting ante-mortem data from the home or place of work of a suspected missing person, this thesis is focused on the collection techniques employed in fingerprinting of deceased individuals (gaining a post-mortem data set) and the techniques of finger mark collection will not be discussed in detail. However, references such as Centre for Applied Science and Technology (2014), Bleay *et al.* (2017), and Forensic Science Regulator (2017a,c) provide an overview of techniques currently employed in finger mark visualisation, lifting, and imaging processes performed according to the standards of UK forensic providers.

Fingerprint collection from living individuals is usually performed under controlled circumstances and can be repeated to achieve a desirable quality of friction ridge detail (if the anatomy of friction ridges permits this) (Forensic Science Regulator, 2017c). Depending on the country/law enforcement policies and standards, and the resources available, fingerprints are collected using either ink and paper cards, electronic imaging, or another medium. In the case of collection using ink, a thin layer of ink is deposited on the area of friction ridge skin of interest (usually all ten hand digit pads and palms) and the inked skin is then rolled onto a pre-printed fingerprinting card (Hawthorne, 2008). With electronic imaging, there are Live Scan units (electronic biometric platforms) in operation at police stations or portable scanners used outside of police stations which are nowadays employed by police forces in the UK preferentially to ink (Homeland Security Technologies, 2005; Forensic Science Regulator, 2017c; Home Office, 2018). The procedure is similar to inking as it involves a rolling motion of the digit pads and regions of palms onto the scanner plate or simple touch of the device plate to produce a ‘flat print’ (Forensic Science Regulator, 2017c). In the last few decades, there has been a notable movement away from the more traditional collection of fingerprints from living individuals using ink and cards towards the electronic systems mainly due to the ease and convenience of storage, access (when analysing electronically), database searching, and fingerprint analysis (National Urban Security Technology Laboratory, 2013; Beslay and Galbally, 2015). Using

electronic automated fingerprint identification systems (AFIS) now allows for the convenient transfer of data from scanning devices and their rapid analysis (National Urban Security Technology Laboratory, 2013; Beslay and Galbally, 2015).

Fingerprint collection from deceased individuals follows similar methods to those used for fingerprint collection from living individuals but brings additional challenges. As the focus of this thesis is oriented more on the analysis of fingerprints collected from deceased individuals, this topic will be discussed in more detail in the following section.

2.5.1.1 Fingerprint collection from deceased individuals

Post-mortem collection of fingerprints is performed to establish or confirm the identity of deceased individuals. The right for identity even after death is recognised as a human right (U.N. GAOR, 1948) and the family of the deceased also has the right to be informed about what happened to their relatives (International Committee of the Red Cross, 2004; Black *et al.*, 2010). Where possible and when friction ridge skin characteristics are present, collection of fingerprints is advised in all cases involving the identification of the deceased; the collection process is considered to be a part of pre-autopsy procedures (National Crime Agency, 2010; Armstrong and Erskine, 2018). Identification based on fingerprint comparison is amongst the quickest and cheapest method of identification and is considered to be a primary approach to identification (along with the comparison of DNA and odontological comparison) (Cattaneo *et al.*, 2006; Czubak *et al.*, 2015; Khoo *et al.*, 2016). As described in section 2.3.4 the human body undergoes numerous changes after death (Gahr *et al.*, 2013; Czubak *et al.*, 2015; Caruso, 2016). The post-mortem and circumstantial changes that affect the collection of fingerprints include rigor mortis, wrinkling as a result of immersion (“washerwoman’s hands”), skin desquamation, complete skin degradation as a result of advanced putrefaction, mummification, saponification (adipocere formation), trauma and carbonization (Reh, 1984; Kahana *et al.*, 2001; Cattaneo *et al.*, 2006; Czubak *et al.*, 2015; Caruso, 2016; Armstrong and Erskine, 2018; Morgan *et al.*, 2018). Collection of high-quality fingerprints from the deceased therefore can present a challenge in comparison to the collection of comparative fingerprint material from living individuals, due to the various

conditions in which deceased individuals are found (Czubak *et al.*, 2015). The condition of the friction ridge skin in deceased individuals will dictate the various techniques that should be used to record friction ridge detail for identification purposes (Cutro, 2011). This section will therefore describe techniques that are used for the collection of fingerprints from deceased individuals, a procedure that depends on the preservation of the soft tissues of the body.

The work of Mulawka (2014) offers an overview of a workflow for collection of fingerprints from deceased individuals. The overview will be briefly introduced and some of the more frequently used techniques will be then described in the following paragraphs in more detail. In her work, Mulawka (2014) states that if the friction ridge skin is intact the fingerprints are collected using the techniques employed in living individuals, such as ink, powder, and digital capture. In cases when the friction ridge skin is compromised, various skin reconditioning techniques are employed. For macerated and decomposed extremities, Mulawka (2014) recommends either 'de-gloving' (removing of the epidermis) and recording the maximum of each of the skin layers using ink, powder, and/or digital capture, or injection of a tissue filler which would create a friction ridge surface suitable for fingerprint collection using ink, powder, and/or digital capture. In case of desiccated and thermally modified friction ridge skin, Mulawka (2014) recommends using rehydration techniques applied to removed digits and/or extremities followed by fingerprint collection using ink, powder, and/or digital capture. In cases when the friction ridge skin is damaged and treated with reconditioning techniques, traditional fingerprint recording strategies, such as ink, powder, and digital capture, might not be sufficient and alternate recording strategies – casting of the friction ridge skin and specialised macro photograph – might be required.

Traditional techniques for the collection of fingerprints from the deceased involve the use of ink or powder and fingerprinting cards which are usually stored as a hard copy or alternately, they may be photographed/scanned and stored as digital data (Hawthorne, 2008; Cutro, 2011; Khoo *et al.*, 2016). To recover fingerprints using ink, the palmar surface of the digits and palms (even plantar surfaces of feet) are covered with a thin layer of ink and pressed or rolled onto the surface of a card. This technique may be problematic to use on hands clenched by rigor

mortis or on those with pugilistic contractures due to exposure of the body to high temperatures (Cattaneo *et al.*, 2006; Rutty *et al.*, 2008). In both cases, such a pose can be “broken”, but procedures which could cause alteration and loss of friction ridge skin characteristics should not be applied (Kahana *et al.*, 2001). In some cases, a specialised spatula with a thin layer of ink can be used to help with fingerprinting of digits which are flexed due to *rigor mortis* but even this tool does not guarantee absence of distortion in friction ridge impressions (Cutro, 2011). In situations where the friction ridge skin has separated from the digit due to putrefaction, it is possible to carefully place the removed, cleaned and dried piece of the skin on top of the operator’s glove and ink and print the skin as if it was still attached to the digits (Cutro, 2011). Increased caution is advised in cases of separated friction ridge skin, as the fragility of such skin influences the quality of any impression. Therefore, soaking of removed skin in a 10 – 15% solution of formaldehyde could be considered to increase the firmness of the removed friction ridge skin and subsequently the efficiency of the technique (Cutro, 2011; Mulawka, 2014). The use of ink was also mentioned in fingerprint collection from the underside of the epidermis in cases where the epidermal surface of friction ridge skin did not yield impressions with sufficient details (Campbell, 2010; Cutro, 2011). Furthermore, the quality of inked fingerprints may be influenced by skin surface hardening due to mummification and desiccation. Czubak *et al.* (2015) stress the importance of using the correct amount of ink in any case where the inking method is applied. According to Principe and Verbeke (1972) and Morgan *et al.* (2018), the use of powder for fingerprint collection from deceased individuals is superior to the inking method. Principe and Verbeke (1972) used black fingerprinting powder and opaque white pressure-sensitive lifting tape, a technique originally described by Thomson (1971). They concluded the ridge characteristics on fingerprints obtained from the deceased by the powder method are clearer than those obtained by the ink method, and that the powder method is also more suitable for individuals with fine or worn ridge detail and it is preferable for obtaining palm prints due to its ease of application. Furthermore, Principe and Verbeke (1972) demonstrated a successful collection of readable dermal fingerprints from burnt digits using this powder method. Collection of dermal fingerprints is considered to be more difficult than the collection of epidermal friction ridge skin fingerprints due to increased fragility and decreased pressure resilience of dermal skin in contrast to the epidermal friction ridge skin;

furthermore there can be a decreased depth between the dermal papillary ridges and dermal grooves which decreases the contrast between the ridges and valleys in dermal friction ridge skin impression (Plotnick and Pinkus, 1958; Chacko and Vaidya, 1968; Misumi and Akiyoshi, 1984; Okajima, 1984; Mizokami *et al.*, 2015). Morgan *et al.* (2018) advocate the use of powder and white adhesive address labels as a preferred method of fingerprint collection from deceased individuals because it is fast, cheap, and easy to perform with a reduced tendency towards print distortion when compared to the ink method. Further advantages of this method include potential use in prominent hand rigor mortis and the potential for obtaining high-quality foot and palm prints. Czubak *et al.* (2015) further demonstrated that substitution of ink by powder and treatment of the decedent's skin by glycerine prior to powder application yielded better results than inked fingerprints. Despite the advantages of powder over ink, collection of fingerprints from deceased individuals presents a challenge even when using powder. Principe and Verbeke (1972) stress the importance of skin surface cleaning and degreasing prior to powder application and fingerprint lifting. Morgan *et al.* (2018) also report moist skin surface (skin after immersion, in advanced decomposition state, with liquid seepage) as presenting potential difficulties when collecting fingerprints using powder.

Another problematic body condition for the collection of high-quality fingerprints from the deceased using ink is skin wrinkling. This condition is also called laundress or "washerwoman's hands" and is caused by body immersion in liquid and is found in advanced putrefaction. It can be accompanied by seepage of bodily/putrefaction fluids through sweat pores and other open lesions on the skin surface (Okajima, 1984; Reh, 1984; Morgan *et al.*, 2006, 2018; Mizokami *et al.*, 2015). The use of ink for collection of fingerprints in the aforementioned conditions does not tend to yield high-quality fingerprints due to the low adherence of ink to the friction ridge skin and subsequent smudging of a fingerprint when pressed/rolled/lifted (Morgan *et al.*, 2018). After skin wrinkling, the skin of bodies immersed in liquid eventually loses the connection between the epidermis and dermis and the dermis is exposed in a process called epidermal desquamation (Weber, 1982; Reh, 1984; Weber and Laufkötter, 1984; Pueschel and Schneider, 1985). However, there are cases where despite the occurrence of epidermal desquamation the epidermis remains relatively coherent and can

create a ‘glove’ for recovery of epidermal fingerprints (Cutro, 2011; Mulawka, 2014). For example, Khoo *et al.* (2016) report successful identification of six bodies in early decomposition stages recovered from a river in Malaysia using the ink method. Although the bodies demonstrated epidermal desquamation, the experts recovered degloved epidermal friction ridge skin, dried the surface of degloved skin, sprayed it with fingerprint ridge builder developed by TriTechForensics, and made inked fingerprints by slipping the degloved skin on their gloved digits and pressing it on fingerprinting cards. In one of the six cases Khoo *et al.* (2016) also successfully applied the inking technique on the exposed dermal layer of the second digit, as it was the only remaining source of ridge detail skin, with the use of ink and clear lifting tape instead of fingerprint cards which demonstrated the possibility of collection of dermal fingerprints when the epidermis is too degraded for collection of epidermal fingerprints. According to Mulawka (2014), friction ridge skin of the dermis and subsequent collection of dermal fingerprints using ink/powder/scanner/photography can be enhanced using boiling technique (osmotic rehydration). This technique consists of up to three short dips (5 – 10 seconds) of hand/digits in boiling water and was used in successful collection of dermal sets of post-mortem fingerprints in multiple DVI situations (Uhle and Leas, 2007; Mulawka, 2014).

Another technique of fingerprint collection from the deceased is photography (Kahana *et al.*, 2001). The National Crime Agency recommends photographing the hand and digit surfaces of the deceased before any manipulation and treatment connected to fingerprinting, since the fingerprint recovery methods can damage the skin resulting in loss of information (National Crime Agency, 2010). The photographs may not be used in the actual comparison if fingerprints of sufficient quality are recovered, but should always be taken to the best standards (correct lighting – usually oblique, correct camera equipment and settings) and can be further enhanced by the application of powders to enhance friction ridge skin (aluminium powder for blackened mummified digits, black powder to enhance shallow ridges of individuals with pale skin) (Kahana *et al.*, 2001). Advantages of photography are that it can be used on bodies in all stages of decomposition, it presents ease of digital information storage, gives the possibility of fast and remote comparison, and since photography is a necessary part of the entire identification process anyway it is also highly likely the equipment for

fingerprint collection using photography will be available even in challenging field conditions (Kahana *et al.*, 2001; Cattaneo *et al.*, 2006; Khoo *et al.*, 2016).

With the introduction of electronic devices into biometric recognition processes, various scanners and fingerprint readers have begun to be involved in identification based on fingerprints (Rutty *et al.*, 2008). Garrett (2006) mentions the use of a Live Scan device for recording fingerprints from the deceased resulting in identification in 43 cases out of 421 sets of fingerprints. According to Garrett (2006), the Live Scan unit has multiple advantages over powder fingerprints including the faster speed of image acquisition and the possibility of remote comparison. A comparison with fingerprints collected using the ink technique is not provided in this publication. Furthermore, Kahana *et al.* (2001) report effective use of a laser-scanner device in cases where charred, mummified and decomposed digits are not suitable for manipulation and chemical treatment due to friction ridge skin fragility. The use of such a device, however, requires severing digits which is a practice that is not considered ethical within the UK and is not recommended (it should only happen in extreme situations) by the UK Missing Persons Bureau and the National Crime Agency (National Crime Agency, 2010). Rutty *et al.* (2008) advocate the use of handheld electronic devices for bodies contaminated with hazardous chemical, biological or radiological agents. Minimized contact with potentially infectious bodies in addition to the possibility of obtaining results quickly are advantages of this fingerprint collection technique (especially in DVI situations); in practice, however, the devices in the UK are still quite expensive and not as effective in obtaining high-quality fingerprints from the deceased as the powder method (personal communication, J. Scott 2019). The quality of fingerprints acquired by handheld electronic devices in Rutty *et al.* (2008) was dependent on the age, gender, and state of decomposition and their results differ to those of Garrett (2006) demonstrating the limitations concerning body condition and availability of handheld electronic devices. More positive and promising results in the use of digital capture devices in the identification of the deceased are reported by Johnson and Riemen (2019). They used an electronic scanner called dead-scan only recently developed by Dutch forensic scientists for use in a DVI situation, and reported successful identification of 151 individuals (out of 298 casualties) via fingerprint comparison.

Another method for fingerprint collection from the deceased is casting. Here, an inverted reproduction of friction ridge skin is produced by application of casting materials such as a wax-based compound, modelling clay, or dental casting materials to the skin surface of the deceased (Saviano, 2000; Kahana *et al.*, 2001; Porta *et al.*, 2007). The use of this technique was reported as effective on mummified remains and bodies where the skin was not fragile or excessively moist due to advanced decomposition (Porta *et al.*, 2007). Caution needs to be exercised, as some casting materials are reported to introduce artifacts to the fingerprint (Ulmansky *et al.*, 1986). Also, depending on the casting material used, this technique usually requires more time and experienced collecting personnel compared to the powder or inking method (Misumi and Akiyoshi, 1984; Ulmansky *et al.*, 1986). However, it can be very efficient, especially in connection with cast visualisation by scanning electron microscope (Misumi and Akiyoshi, 1984).

There are other techniques of fingerprint collection from the deceased that are available, but they are more expensive, time-consuming, require specialised equipment or detachment of digits from the body. These are for example acquisition of thanatoprints by injection of specific embalming solution into digital volar pads (Gahr *et al.*, 2013), injection of hot paraffin, gelatine, water, or glycerine into digital volar pads (Principe and Verbeke, 1973; Mulawka, 2014; Czubak *et al.*, 2015), ionic rehydration (Kahana *et al.*, 2001; Fields and Molina, 2008), radiography (Kahana *et al.*, 2001), illumination of dissected digital pad with a bright light source (Morgan *et al.*, 2019), and other chemical treatment to restore/enhance friction ridge skin appearance (Richardson and Kade, 1972; Okajima, 1984; Sanz, 1994; Chen *et al.*, 2017). These techniques are less commonly used in practice and therefore this study will not be focused on them.

2.5.2 Examination

Following the collection, and any necessary visualisation and imaging procedures in the case of finger marks, friction ridge skin detail is examined by trained experts. The principle of examination lies in the comparison of the finger mark or fingerprint of unknown origin with fingerprints of known individual/s to provide an opinion on identification outcome (Vanderkolk, 2011; Adam, 2016). As summarised in Champod and Chamberlain (2009) there are three situations where examination of friction ridge skin is undertaken in the UK legal system:

comparing a print to prints (collected from living/dead individuals against a database of known prints to establish the identity of individual), comparing mark to prints or *vice versa* (a mark left in circumstances of interest compared to a database of prints from a known source, prints from known source against a database of unresolved marks), and marks to marks (marks collected under different circumstances to investigate possible connections).

During the examination, experts are looking for similarities and differences in the three levels of detail present in friction ridge skin; these are described in section 2.4.1. The examination is undertaken following the analysis, comparison, evaluation, verification (ACE-V) method, which is a sequence of protocols adopted by forensic science fingerprint examiners worldwide (Ashbaugh, 1999; Vanderkolk, 2011; Scientific Working Group on Friction Ridge Analysis Study and Technology, 2013; Forensic Science Regulator, 2017b, 2017c).

The ACE-V process was also adopted in the UK and the protocol will be described in detail from the perspective of UK forensic standards and regulations (Forensic Science Regulator, 2017b). This set of protocols does not describe a strictly linear process, but a cyclic iterative process with the flexibility to return to certain steps repeatedly if there is a need for it. An example of the ACE-V process which is followed in the USA by fingerprint examiners is included in Figure 2.5.1 (Expert Working Group on Human Factors in Latent Print Analysis, 2012).

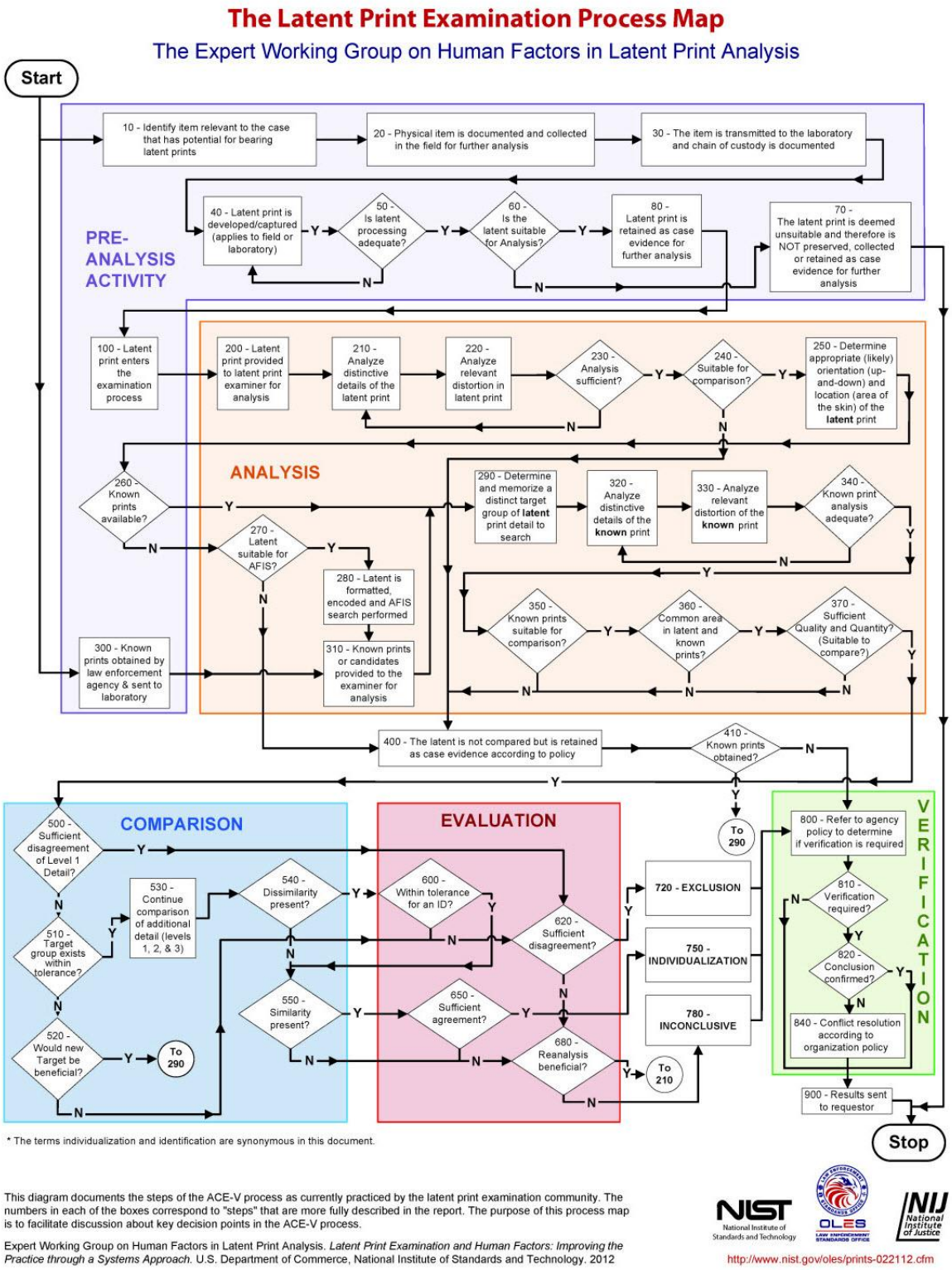

Figure 2.5.1 Example of the ACE-V process flowchart followed by fingerprint examiners in the USA. Taken from Expert Working Group on Human Factors in Latent Print Analysis (2012).

According to the UK Forensic Science Regulator (2017a), the analysis part of ACE-V includes an assessment to determine the suitability of the impression for comparison purposes. The examiner's decision about whether an impression is suitable for further steps of analysis is made based on the quantity and quality of

the friction ridges of a given impression. None of the currently published Forensic Science Regulator Codes of Practice and Conduct include specific definitions of quality levels when assessing quality and clarity of friction ridges and their details (Forensic Science Regulator, 2017b, 2017c, 2017a). The Forensic Science Regulator (2017b) cites American National Standard for Information Systems, (2015) when referring to assessing quality/usefulness of biometric data for automated recognition, however, the original publication only deals with the image quality as assigned by the software rather than the assessment performed by the expert. The assessment of each friction ridge impression performed by experts is therefore a subjective assessment for every examiner. The UK Forensic Science Regulator of England and Wales (2017b) states that sufficiency of friction ridge detail quantity and quality exists when it reaches what she describes as a practitioner's threshold and when a conclusion/outcome can be made from the observation of the detail. The Forensic Science Regulator (2017a) further notes that when encountering an insufficient quality of friction ridge detail (and/or also poor quality of exhibits on which finger marks might be deposited), meaning that any friction ridge is not subjected to final evaluation and/or verification the reasons need to be documented. In Scotland, the Scottish Police Authority (SPA) also does not include any specific quality levels definitions in their standard operating procedures apart from the minimum number of eight minutiae required for impressions to be uploaded onto the IDENT1 automated fingerprint recognition system (personal communication, B. Robertson 2019). Apart from the numerical criterion required by the software, there are two other quality levels the experts of SPA assign to each print before proceeding to the next step of ACE-V, and those are designated 'insufficient' and 'sufficient for manual comparison' and are assigned by the fingerprint examiner. This analysis step of ACE-V lacks any defined ranking of friction ridge skin impressions as a function of their quality level, highlighted by numerous reports and papers (Expert Working Group on Human Factors in Latent Print Analysis, 2012; Neumann *et al.*, 2013; Ulery *et al.*, 2013, 2014; Champod, 2015). The main criticism of the current process is aimed at the lack of consistency and reproducibility due to the subjective nature of quality assignment to friction ridge skin impressions (Schiffer and Champod, 2007; Dror *et al.*, 2011; Ulery *et al.*, 2015). Researchers have already explored an automated analysis of quality and formalisation of quality assessment (Hicklin

et al., 2013), but UK regulations for friction ridge skin analysis have not implemented it as of yet.

Once the expert deems the friction ridge skin impression of sufficient quality to proceed, comparison – the second step of the ACE-V process, can be performed. A side-by-side comparison of two friction ridge impression areas is performed to determine the level of agreement between the two sets of information and identify the existence of any discrepancies and similarities (Champod and Chamberlain, 2009; Vanderkolk, 2011; Forensic Science Regulator, 2017b). In the UK, the comparison can be done manually using hard copy images or it can be computer-based using digital on-screen images (Forensic Science Regulator, 2017c, 2017b). It is at this stage of the ACE-V process where standards for establishing identification will influence the process most predominantly.

There are two different approaches to what is required for an 'identification' currently employed worldwide. A numerical standard requires a set number of minutiae (between 7 to 17) to be matching in two compared areas of friction ridge skin for an identification to be made by examiners (Champod and Chamberlain, 2009; Adam, 2016). The second standard is non-numerical or holistic, has no minimum number of matching characteristics necessary and includes the whole range of ridge features in the comparison process and eventually in identification outcome (Ashbaugh, 1999). Therefore, some aspects of comparison during ACE-V may differ slightly depending on which standard each specific country is using. In the numerical approach, the experts count the matching minutiae and once they reach the 'threshold' of sufficient matching minutiae without any observed discrepancies, the identification is made. In the holistic approach, no counts of minutiae are reported, and even though the minutiae might be counted the examiners use all the observable information available for comparison purposes: pattern, ridge flow, and minutiae counting (Adam, 2016). Furthermore, using the holistic approach identification will be declared if there are no dissimilarities and a sufficient level of agreement across the three levels of legible features (Champod and Chamberlain, 2009). Using a numerical standard was an attempt to add a scientific and empirical basis to the friction ridge evidence type (Adam, 2016). However, as stated by Adam (2010) neither the numerical thresholds nor any of the currently devised statistical evaluation methods for friction ridge skin

impression prove the uniqueness of a fingerprint or a finger mark. Moreover, Neumann *et al*. (2006, 2007), Champod and Chamberlain (2009) and National Research Council (2009) claim that there is no valid logical and/or statistical basis for a pre-determined minimum number of friction ridge minutiae to establish identification outcome. In the UK, the switch from the threshold of 16 matching minutiae to the holistic approach was made in 2001 (England and Wales) and 2007 (Scotland) following the reports made by Evett and Williams (1996) (Campbell, 2011), which stated that due to considerable variability in the number of minutiae identified by examiners in a finger mark the 16-point standard was not an efficient measurement quotient of quality. The threshold for identification was replaced by the opinion of qualified examiners and the ability to identify sufficient similarities and no discrepancies between the mark/print and the print being verified by another two examiners (Leadbetter, 2005; Adam, 2016). Other countries using the holistic approach include the USA, Canada, Australia, Switzerland, and Scandinavian countries; the countries of south and central Europe, and South African still utilise the numerical approach (Adam, 2016; Champod *et al.*, 2016).

The last two steps of the ACE-V process are evaluation and verification. Evaluation is an assessment of the value of details observed during the first two processes – analysis and comparison (Vanderkolk, 2011; Forensic Science Regulator, 2017b). The evaluative assessment leads to the formulation of a conclusion which is then reported (Champod and Chamberlain, 2009). In UK practices, verification of the whole examination by two further experts is rooted in the process as an ultimate quality assurance measure (Champod and Chamberlain, 2009; Campbell, 2011; Forensic Science Regulator, 2017b). Verification means re-examination of the same friction ridge impression items using the ACE protocol (Vanderkolk, 2011) and according to Adam (2016), all three examiners need to agree on the outcome before it can be presented in court in the UK. In the Forensic Science Regulator's report (2017a) it is stated that the verification step can be performed 'blindly' (no knowledge of the outcomes from the prior examiner, no additional knowledge of the case) or openly (there is knowledge of the conclusions made by the original practitioner). According to Champod and Chamberlain (2009), each department anchors the specific steps of verification in their own standard operating procedures. They further state that

it could mean the concept of independent review might be questioned in some small-sized departments (i.e. staffing, resources). Questioning the reliability of forensic providers analysing friction ridge skin evidence without acceptable basic quality standards is a problem which has been brought up recently by the Forensic Science Regulator for England and Wales, Gillian Tully, in her report on the state of forensic science disciplines (Tully, 2019; Devlin, 2020).

2.5.3 Reporting

As stated by the Forensic Science Regulator (2017a), after examination of friction ridge skin impressions qualified practitioners report the outcomes of their examination as an opinion based on their observations not a statement of fact, which was also one of the key recommendations stemming from the Fingerprint Inquiry reviewing fingerprint evidence in Scotland (Campbell, 2011). There are currently four main outcomes of examination of friction ridge skin impressions reported by the forensic providers of England and Wales: insufficient, inconclusive, identification, exclusion (Forensic Science Regulator, 2017b). All four outcomes are defined in publications of Forensic Science Regulator (2017a, b), the guidelines are also followed by Scottish fingerprint examiners (personal communication, J. Scott 2018).

- The *insufficient outcome* is reported when the quantity and/or quality of compared areas of friction ridge detail is/are poor and it would not be reliable to proffer any other decision.
- The *inconclusive outcome* is reported when the level of agreement and or disagreement between the compared friction ridge skin impression areas is such that it is not possible either to conclude that they originated from the same donor, or to exclude the particular individual as a source for the unknown impression. In both cases of reporting (insufficient and inconclusive), an explanation must be provided to support the claim.
- *Exclusion outcome* is reported in cases of sufficient quality and quantity of friction ridges, and sufficient disagreement between two compared areas of friction ridge skin impressions; a conclusion is made that the friction ridge impressions did not originate from the same individual.
- The *identification outcome* is reported in cases in which two areas of friction ridge skin impression contain friction ridges of sufficient quality and quantity and there is an agreement with no unexplainable differences between the

two areas. The identification outcome is reported as the opinion of the practitioner that two areas of friction ridge detail were made by the same individual.

Numerous scientists have criticised forensic examination of friction ridge impressions because of this categoric way of evidence reporting and since the publication of the NRC report on the state of forensic science disciplines in the USA, the community of experts involved in friction ridge impression analysis have admitted the need for a change (Neumann *et al.*, 2006, 2007, 2013; Champod and Chamberlain, 2009; Cole, 2009; National Research Council of the National Academies, 2009; Campbell, 2011). The criticism lies in the 'leap of faith' from probabilistic mental processes employed during the evaluation phase of ACE-V to a sudden categorical certainty of opinion during court presentation (Adam, 2016; Champod *et al.*, 2016). Although suggestions for probabilistic evaluation and inclusion of a more transparent spectrum of conclusions in reporting of the friction ridge evidence type do exist in research circles (Neumann *et al.*, 2006, 2007; Champod *et al.*, 2016; Leegwater *et al.*, 2017; Swofford *et al.*, 2018), successful implementation of the proposed changes in the reporting process of practitioners have been identified as still lacking in some courtrooms and forensic science codes of practice (Cole, 2014; Edmond *et al.*, 2014; Hoy, 2018; Tully, 2019; Devlin, 2020; Nic Daeid *et al.*, 2020).

It is also important to note that opinion presentations of fingerprint evidence in court could be influenced by quality of materials examined and the subjective view of fingerprint quality/sufficiency, experts' ability to observe detail in mark and print reliably, experts' subjective interpretation of observed characteristics, and the bearing of explanations for any potential differences between fingerprints (Campbell, 2011; Adam, 2016). Numerous studies and reports have shown that the reporting of fingerprint comparison outcome is influenced by the implementation and execution of the ACE-V process during fingerprint examination (Campbell, 2011; Ulery *et al.*, 2011, 2012, 2013, 2014; Neumann *et al.*, 2013). As mentioned in the Scottish Fingerprint Inquiry Report, the importance of meticulous and accurate record keeping goes alongside with consistent implementation of ACE-V process, but it is crucial that fingerprint examiners acknowledge that fingerprint evidence is not infallible due to the human factor

employed, especially in the case of complex marks (Campbell, 2011). Furthermore, it is important to highlight the need for a change in reporting of the fingerprint evidence as it was suggested by Champod *et al.* (2016). They advocate the use of probabilistic tools (Bayesian networks) which would allow for expert's reports being supported by mathematical models indicating evidential weight instead of opinions regarding the identity of fingerprint source based on experience, albeit verified by other experts.

2.6 Use of dermal skin layer in identification process

2.6.1 Relationship between dermal and epidermal fingerprints

The dermal layer of friction ridge skin can be used for the identification of deceased individuals in cases when an epidermal skin layer is no longer available for fingerprinting (Plotnick and Pinkus, 1958; Ferguson, 1966; Okajima, 1984; Black *et al.*, 2010; Mulawka, 2014; Mizokami *et al.*, 2015). The alteration, degradation, or complete loss of the epidermal layer of friction ridge skin may occur as a result of advanced post-mortem decomposition; processes affecting the skin include maceration, desiccation, mummification, burning, and putrefaction (Plotnick and Pinkus, 1958). According to Mulawka (2014), out of 172 cases of post-mortem fingerprint collection performed at the New York City Office of Chief Medical Examiner, dermal fingerprints were collected for identification purposes in 27% of cases. In cases where the epidermal friction ridge skin layer of a deceased individual is damaged beyond its usefulness, it is suggested that comparison of post-mortem dermal fingerprints and ante-mortem epidermal fingerprints can result in an identification (Mizokami *et al.*, 2015). Such comparison is possible due to the relationship between the two friction ridge skin layers shown by multiple studies researching dermal and epidermal friction ridge skin (Plotnick and Pinkus, 1958; Chacko and Vaidya, 1968; Okajima, 1979; Misumi and Akiyoshi, 1984) and described in sections 2.2.1, 2.2.2, and 2.3.1 of this thesis.

According to the observations of Plotnick and Pinkus (1958), the fingerprint collected from the dermal skin layer is identical to the fingerprint collected from the epidermal skin layer in all aspects except for the 'split' or doubled and finer appearance of dermal ridge impressions. As confirmed by their photographic and histological exploration of the dermal skin layer, underneath each epidermal ridge

of the epidermal friction skin layer there is a double row of dermal papillae, these are what provides the split or doubled appearance (Figure 2.6.1).

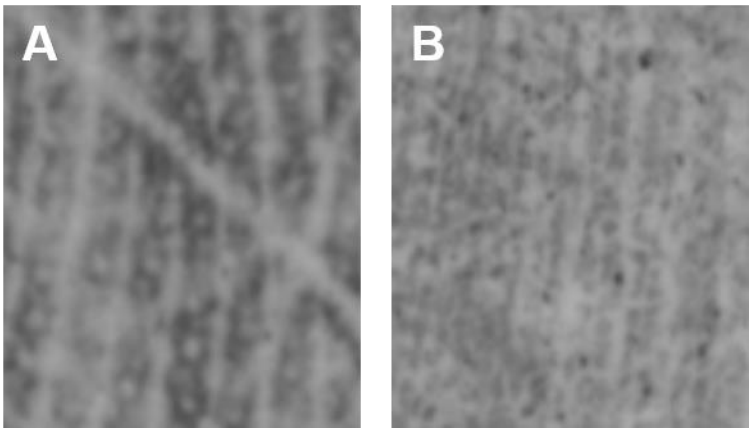

Figure 2.6.1 Fingerprinted section of epidermal (A) and dermal (B) layer of the same friction ridge area.

Chacko and Vaidya (1968) extended the exploration of dermal-epidermal friction ridge skin relationships to friction ridge skin from the whole palmar and foot plantar surfaces from two individuals, one described as ‘new-born’ and the other as ‘old’ (cited in their material and methods section). They categorised the appearance and configuration of dermal papillae in friction ridge skin into three groups according to the position of sweat pores and the depth of papillary grooves (see section 2.2.1). They found some differences in the appearance of dermal papillae between the various friction ridge locations as well as between the two studied individuals. Their findings pose implications for identification based on the dermal skin layer since it suggests that the quality and clarity of ‘double-ridged’ dermal fingerprint impressions might vary individually and will depend on a location within the boundaries of volar skin. Their findings are, however, based on observation of samples from two individuals which is an extremely limited sample size and therefore cannot be generalised.

Okajima (1979) in his study on 36 bodies from individuals between the age of 40 and 80 years also studied the dermal friction ridge skin of palmar and foot plantar surfaces. He also observed a variation in the arrangements of papillae in the ridges and defined these as falling into two categories: a simple double-row arrangement or a crowded arrangement (Figure 2.6.2). From the perspective of dermal fingerprint examination, the crowded papillae arrangement can be harder

to follow during the analysis and comparison process. Okajima (1979) studied the variation of dermal papillary appearance within different locations of human palm and foot sole. Although the crowded arrangement of dermal papillae was proportionally more evident in other parts of palmar and plantar friction skin, it was also found in 18 out of 37 cases of digital apex friction ridge skin, which shows that such crowded arrangement of dermal papillae can be present in dermal fingerprints especially in individuals of advanced age (Okajima, 1979). Moreover, the same study provided evidence of dermal papillae proliferation into the dermal furrows, which may not only obscure the clarity and appearance of the dermal fingerprint but also indirectly contribute to the flattening of the epidermal ridges which can influence the quality of epidermal fingerprints. The ingrowth of dermal papillae into the dermal furrows could decrease the depth of epidermal furrows contributing so to the flattening of epidermal ridges in older individuals already caused by the loss of skin elasticity in advanced age. Furthermore, as already mentioned in section 2.3.1 of this thesis, a study by Stücker *et al.* (2001) found an increase in the occurrence of interstitial epidermal ridges (which are an epidermal demonstration of papillary proliferation within the furrow region of the dermis) with increasing age of individuals. However, since the changes occur in both the dermal and epidermal friction ridge skin layer, they should not have an impact on the potential comparison of dermal and epidermal fingerprints, providing that a reasonably short time has elapsed between collection of both sets. Similarly, Misumi and Akiyoshi (1984) in their study, which supports the proliferation and multiplication of dermal papillae with increasing age, interpret their findings as demonstrating that there is the possibility for changes even in the type of dermal friction ridge skin minutiae as a result of the papillary proliferation and multiplication. They do admit, however, that more research is needed to confirm this. More importantly, they give evidence for the fact that the multiplication of dermal papillae can cause loss of ‘dermal surface localisation’ during aging. Together with the study of Okajima (1979), the study of Misumi and Akiyoshi (1984) demonstrated that the dermatoglyphic features of dermal fingerprints collected from individuals of advanced age could be hard to analyse and match to their epidermal counterpart.

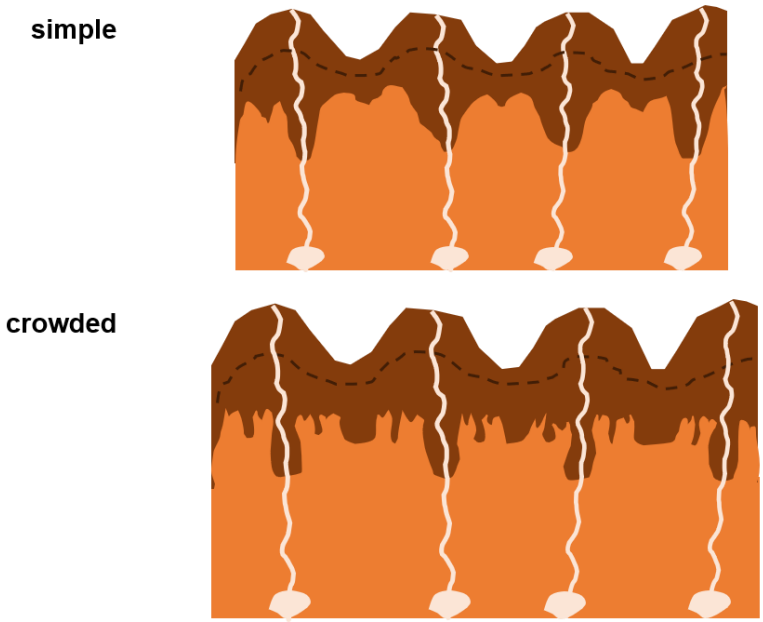

Figure 2.6.2 Schematic showing a cross-section of simple and crowded arrangement of dermal papillae under epidermal ridges.

2.6.2 Comparison of dermal and epidermal fingerprints: research and case studies

Despite the potential challenges that could arise when examining dermal fingerprints collected from individuals of advanced age due to the reported alterations of the dermal skin layer, there are published cases of identifications based on the comparison of dermal and epidermal friction skin layer. A summary of the cases can be found in Table 2.6.1 and each case/research study is introduced in more detail below.

Table 2.6.1 Literature sources that included cases of epidermal-dermal fingerprint comparisons. NA = answers not provided.

Reference	Number of individuals	Age range of individuals (years)	Environmental conditions upon body recovery (number of individuals)	Number of items with friction ridge skin examined	Identification possible (number of individuals if different to original number)
Plotnick and Pinkus (1958)	3	NA	Immersed in water (1) Amputated digits (2)	NA 1	Yes
Ferguson (1966)	1	NA	Humid atmosphere in a ship cargo hold	All hand digits	Yes
Principe and Verbeke (1972)	1	NA	Fire	1	Yes
Okajima (1984)	4	24-78	See Table 2.6.2	14	Yes (3)
Mizokami *et al.* (2015)	19	NA	NA	19	Yes (16)
Khoo *et al.* (2016)	1	NA	Submerged in water	1	Yes

In addition to their histologic study of the dermal-epidermal friction ridge skin relationship, Plotnick and Pinkus (1958) demonstrate the quantitative comparison of an epidermal and dermal fingerprint. The need to perform such comparison stemmed from an actual case of a body found immersed in water which was lacking an epidermis due to degloving. The identification of the body was based on the comparison of dermal post-mortem fingerprints and epidermal ante-mortem finger marks. During the legal proceedings, the court asked the experts to provide evidence that such a comparison of dermal and epidermal fingerprints may yield identification results. The experts were asked to explain the differences between the dermal and epidermal layers of friction ridge skin and provide evidence to the claim that both skin layers shared a comparable pattern of friction ridge skin. To demonstrate this, Plotnick and Pinkus (1958) counted minutiae from both friction ridge skin layers of a single digit coming from an individual who had undergone a recent digital amputation. No information about the digit or age of the individual is included. The skin layers were separated using acetic acid immersion and the authors used the inking method to recover prints from each skin layer and placed their recovered impressions onto fingerprinting cards.

Twenty-one matching minutiae characteristics were found on both epidermal and dermal print and with the minimum of 12 needed for an identification, this surpassed the requirements. No information about minutiae found exclusively on either the dermal or epidermal fingerprint is provided in the publication.

In the case study published by Ferguson (1966), an unidentified decomposing body was discovered in a ship cargo. The friction ridge skin was unsuitable for fingerprint collection as the digits were mummified. The digits were removed from the body to facilitate the rehydration procedure of the friction ridge skin. All hand digits were dipped in a solution of boiling water and glycerine (4%), prior to the treatment incisions were made on either side of digital pads and along the skin of the distal interphalangeal joint. After the treatment, what is reported as the epidermis was peeled away, and the exposed friction ridge detail of the deeper skin layer was photographed for identification purposes. Identification was made upon the comparison of the post mortem photographs of friction ridge skin with ante mortem fingerprint set. No information on about the comparison procedure was published.

Principe and Verbeke (1972) collected dermal fingerprints from one fire-damaged right thumb (they received three digits in total, but two of them were too damaged) of an unidentified victim. The epidermis of the digit was completely damaged by burning and the dermal friction ridge skin layer was exposed. The friction ridges were photographed, the skin was inked, and a fingerprint was taken. Despite the ink fingerprint being classified as suitable for identification, dusting and lifting of the fingerprint using powder was also performed and the fingerprint collected using the dusting-tape method was classified as superior to the inked fingerprints as they contained more identifiable “points”. The individual was positively identified based on the comparison of the post-mortem dermal fingerprint and ante-mortem inked fingerprint record.

Okajima (1984) describes four case studies of identifications made based on the dermal skin layer. He examined body parts containing friction ridge skin collected from four unidentified bodies (Table 2.6.2). In his study, he also proposes a method of friction ridge skin chemical treatment with an alkaline solution and toluidine staining which enhances the visibility of dermal papillary ridges.

Photography was used to capture the stained dermal friction skin and minutiae characteristics. In a total of eight friction ridge skin samples in various stages of post-mortem decomposition, there is no record of recognisable minutiae captured from the dermal skin layer before the chemical treatment. In four out of the eight cases, the minutiae are recognisable for identification purposes after the chemical treatment.

Table 2.6.2 Summary of cases where the dermal skin layer was used for the identification of bodies in Okajima (1984).

Case	Age	Sex	Time since death	Where, when found	Samples collected	Skin layer condition before treatment	Dermal BEFORE treatment	Treatment	Dermal AFTER treatment
1	69 years	female	22 days	Moist brush, autumn	Left index finger	½ contains exposed damaged dermis, ½ contains attached epidermis	Not useful	Epidermis removal, formalin fixation, alkaline solution, staining	Useful (15 minutiae identified)
					Left middle finger	Epidermis almost all lost	Not useful	Staining, alkaline solution, epidermis removal	Some minutiae displayed
					Right index finger	Epidermis almost all lost, dermis damaged by post-mortem decomposition	Core pattern recognised	Alkaline solution, epidermis removal, staining	No minutiae displayed
					Other digits (7)	3 digits no signs of epidermis and dermis almost all gone, 4 digits entire ridge detail skin damaged	Not useful	Not treated	NA
2	78 years	male	7 days	Submerged in the sea, winter	Right hypothenar area	Epidermis completely separated	Not useful	Alkaline solution, staining	Not useful
					Right ring finger	Macerated epidermis attached	Not useful	Formalin fixation, epidermis removal, alkaline solution, staining	Useful, remarkable quality
3	24 years	female	17 days	On the ground, winter	Distal phalanx of a digit	Epidermis partially separating, in some places tightly adhering (epidermal inking possible)	Not useful	Alkaline solution, staining	Useful only in places where epidermis chemically removed
4	54 years	male	5 days	Indoors at home	Distal phalanx of a digit	Epidermis completely separated	Not useful	Staining, alkaline solution	Not useful, no minutiae identified

Another case report which involved the identification of a deceased individual via the comparison of dermal and epidermal fingerprints was presented by Khoo *et al.* (2016). They report on six bodies recovered from a river after a helicopter crash. The identification process of all bodies was performed by fingerprint comparison. Five bodies were recovered after 1-2 days, the last individual was recovered after 4 days spent in water. In the case of the last individual recovered, identification was made by comparing a post-mortem fingerprint from the dermal layer with an ante-mortem fingerprint from national records. The post-mortem dermal fingerprint was collected from the right index finger using the inking method and transferred onto a fingerprinting card or onto a glass sheet but both techniques yielded low-quality fingerprints. The quality of the dermal fingerprint was improved when using ink deposition and subsequent transfer on adhesive tape to fingerprinting cards. The identification was successful once they had the higher quality print, which also proved that collection technique influences the identification outcome when comparing dermal and epidermal friction ridge skin layer.

The most recent and only study which quantified the difference between dermal and epidermal fingerprints in a controlled manner to date was performed by Mizokami *et al.* (2015). They dissected digits from 19 deceased individuals, one digit per individual, and used acetic acid immersion for separation of friction ridge skin layers. They did not include age at death of the individuals involved in the study which is an important factor to consider when dealing with the dermal skin layer as was described in the section above (Okajima, 1979). After the assessment of minutiae numbers in an area of 1 cm^2 on dermal and epidermal fingerprints by a fingerprint examiner, they report more than 60% of observed minutiae as matching. Furthermore, out of 19 cases, they report 3 inconclusive cases of identification and advise the use of more than one digit per individual, if possible, when dealing with the comparison of dermal and epidermal fingerprints.

2.7 From literature review to the current study

As post-mortem desquamation usually occurs in cases and situations not suitable for detailed research (i.e. criminal cases, natural disasters), there is a limited number of controlled research studies dealing with direct comparisons of large samples of dermal and epidermal fingerprints. Although the underlying anatomy is well described, the specific influences of age-related changes regarding the identification process based on dermis are not documented, nor quantified in comparison to what is known about epidermal fingerprints.

The present study not only offers a unique opportunity to add more information to the field of dermal fingerprints in general but also tries to broaden and verify some known facts and assumptions harvested from older research using a larger sample of fingerprints and friction ridge examiners analysing and comparing given fingerprints. Moreover, the inclusion of friction ridge examiners from various countries presents an opportunity to compare numerical and non-numerical standards of friction ridge analyses concerning the comparison of a dermal and epidermal fingerprint. The study also tests the effect of various collection techniques on the quality of dermal and epidermal fingerprints and on the performance of the fingerprint examiners in a controlled way on a large sample of epidermal-dermal fingerprint pairs. The study employs a new model for fingerprint research, Thiel-embalmed bodies, in an ethical way and following UK legal requirements without the need to separate the digits from the body, something which none of the studies mentioned above complied with.

The following two chapters of the thesis describe two separate experimental sections. The first experimental section (chapter 3) was undertaken to confirm if it is the dermal layer which is being exposed as a result of epidermal desquamation in fingerprints collected from Thiel-embalmed bodies. Subsequently, the second experimental section (chapter 4) deals with the epidermal and dermal fingerprints collected from Thiel-embalmed bodies, their comparison by trained fingerprint examiners, and comparison of various fingerprint collection techniques. Each of the two chapters is briefly introduced in the beginning, bringing focus on the research question which has not been answered by previously published material, and each introduction is then concluded by the experiment’s aims. Each chapter contains a separate

discussion section and a summary of the main findings and conclusions from both experimental parts are offered in the fifth chapter of the thesis.

Chapter 3 Histology of epidermal desquamation in Thiel-embalmed elderly individuals

3.1 Introduction

The Thiel embalming method, developed by the anatomist Walter Thiel, preserves bodies by intravascular perfusion and subsequent immersion in Thiel embalming solution (Thiel, 1992). The original embalming solution developed by Walter Thiel contains fixatives (ammonium and potassium nitrates, 4-chloro-3-methylphenol, formaldehyde), disinfectant (boric acid) and plasticity preservative (ethylene glycol) (Thiel, 1992). The Centre for Anatomy and Human Identification at the University of Dundee adjusted the original Thiel formula to lower the concentration of formalin used during embalming (Eisma *et al.*, 2013). The subsequent reduction in exposure to noxious irritating gases is one of the advantages of using Thiel embalming fluids over the more wide-spread use of the formalin embalming method (Balta *et al.*, 2015; Rocha Ferreira *et al.*, 2017). The detachment of the epidermal layer (epidermal desquamation) during immersion is a known 'by-product' of Thiel embalming (Thiel, 1992; Kerckaert *et al.*, 2008; Eisma *et al.*, 2013; Kocbek and Rakusa, 2017). Some authors also mention the formation of bullae, blister-like detachment of the epidermis from the dermis, creating a space filled with fluid (Boaz, no date; Kerckaert *et al.*, 2008). However, minimal specific attention is given to Thiel-embalming-induced epidermal desquamation in the literature. Only Boaz (n.d.) provides histological section evidence of a layer of skin detaching during the Thiel embalming process. He describes superficial epidermal desquamation occurring between the *stratum corneum* and *stratum malpighii* (i.e*. stratum basale* + *stratum spinosum* + *stratum granulosum*)*,* yet by claiming the bullae are formed during Thiel embalming he also indirectly points towards the detachment of the epidermis from the dermis. Additionally, Boaz (n.d.) does not describe the sample size or time of skin sampling when making the histological sections. Thiel (1992) and Eisma *et al.* (2013) do not mention skin histology in connection to Thiel-embalming-induced epidermal desquamation simply stating that the epidermal layer detaches. Likewise, Kerckaert *et al.* (2008) and Kocbek and Rakusa (2017) only mention the occurrence of desquamation of the epidermis in Thiel-embalmed bodies

which indirectly suggests that there is a detachment of the epidermis from the dermis.

The changes occurring during moist desquamation, which may accompany some medical conditions, are caused by the severing of the connection between different laminas within the basement membrane zone of the epidermal-dermal junction, as well as by a failure to produce new cells of the basal layer (Kedge, 2009). A similar process of epidermal-dermal junction degradation is likely to be occurring in Thiel-embalmed cadavers due to the impact of Thiel fluid on proteins (Tennent, 2014). Although Tennent (2014) proved Thiel embalming fluid has little degradation impact on collagen, there are other proteins (e.g. laminin, entactin and proteoglycans) present in the basal lamina on the epidermal-dermal junction which might degrade during the embalming process and cause the epidermal desquamation (Paulsson, 1992). More biochemical research is needed, however, to pinpoint what occurs on a cellular and molecular level during epidermal desquamation caused by Thiel embalming.

As was mentioned in paragraphs above, no specific histological study into epidermal desquamation in Thiel-embalmed cadavers has been published to date, although the fact that epidermal desquamation does occur in Thiel-embalmed cadavers has been mentioned in multiple published studies (Thiel, 1992; Kerckaert *et al.*, 2008; Eisma *et al.*, 2013; Kocbek and Rakusa, 2017). The interval between the embalming and the occurrence of desquamation is reported to vary depending on the body part, although again this has not been quantified (Eisma *et al.*, 2013). However, no data on the sample size and exact time frame regarding the epidermal desquamation occurrence has been given in cited studies. The histological data about the nature of the skin detaching from the cadaver during Thiel embalming are also somewhat conflicting. Boaz (n.d.) reports detachment of *stratum corneum* from *stratum malpighii* during the Thiel embalming process but provides no description of the sample size in their report. Before the collection and closer study of dermal fingerprints collected from Thiel-embalmed bodies can be conducted, histological confirmation is needed whether or not the dermal skin layer is exposed fully or there are still histological traces of the epidermis present after the desquamation occurs to ensure that the fingerprints recovered after desquamation are from the dermal layer.

3.1.1 Aim

The study aims to describe various types of epidermal desquamation observed in histological thick skin sections sampled at various timeframes during the Thiel-embalming process. If the desquamation occurs between the epidermal and dermal layer, the exposure of the dermal layer allows for yet another application of Thiel-embalmed bodies – fingerprint research. The opportunity to collect and compare dermal fingerprints directly to their epidermal counterparts has a research and training potential in areas such as fingerprint collection from deceased individuals and disaster victim identification (Okajima, 1984; Morgan *et al.*, 2006; Mizokami *et al.*, 2015).

3.2 Materials and Methods

3.2.1 Sample

A sample of skin was taken from the left thumb of deceased individuals who had no apparent disruption to their skin or visible skin pathology. No medical information besides the cause of death was available for the sampled individuals; therefore, it was not possible to confirm/refute the absence of a potential skin pathology that was not visible to the naked eye. A standard biopsy skin punch (Ø = 4 mm) was inserted into the centre of the skin on the palmar surface of the distal left thumb (Figure 3.2.1). The tissue column was carefully manually removed (where necessary with the use of forceps) and placed into a plastic container with a lid.

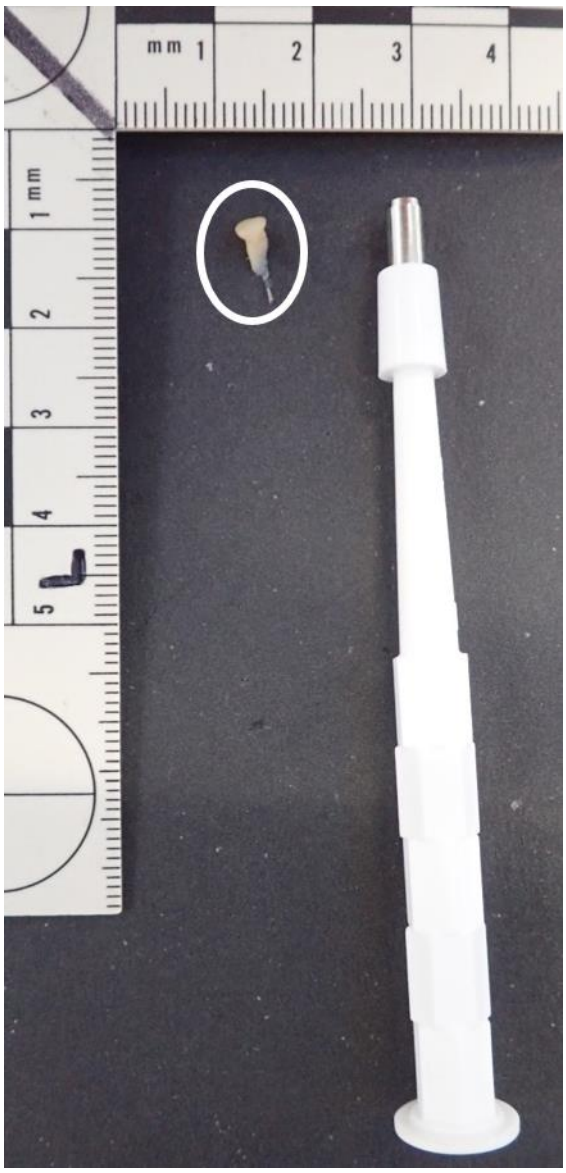

Figure 3.2.1 Photograph showing column of skin tissue (white circle) excised with standard biopsy skin punch on the right side.

Samples were taken from 40 bodies bequeathed to the Centre for Anatomy and Human Identification at the University of Dundee (Table 3.2.1, Table 3.2.2). All procedures performed in the study followed appropriate Scottish legislation [the Anatomy Act 1984 and the Human Tissue (Scotland) Act 2006] and no specific ethical approval was required for sampling of the skin from the bodies. The population used was one of European white origin, with 21 females and 19 males. The mean age at death for females was 83.05 years and the mean age at death for males was 76.21 years. The bodies were embalmed according to the protocol included in Eisma *et al.* (2013), which has been adjusted from the original method published by Professor Walter Thiel (Thiel, 1992), hence the name 'Thiel embalming fluid'. Only one sample was taken from bodies 1 – 20 (Table 3.2.1)

after they had been exposed to between 162 and 258 days of immersion in Theil embalming fluid. Samples taken from these individuals were labelled as 'post-embalming' control. For bodies numbered 21 – 40 (Table 3.2.2), samples were taken before the immersion of the body in the Thiel embalming fluid and then at weekly intervals for between four or six weeks after immersion had occurred; this allowed the study of the effect of time on epidermal desquamation caused by immersion in the Thiel embalming fluid. A four-week (28 days) interval was selected initially (n = 8), however, this time was extended to a six-week (42 days) interval (n = 12) after it became evident that complete epidermal desquamation was not occurring for all bodies after four weeks.

Table 3.2.1 Details about bequeathed individuals sampled as post-embalming controls. NA = not applicable

Individual number	Sex (M = male, F = female)	Age at death	Total number of days in embalming tank
1	F	71	199
2	F	84	202
3	M	88	175
4	F	70	258
5	F	67	226
6	M	83	205
7	F	103	184
8	M	90	176
9	M	78	217
10	M	49	177
11	M	61	175
12	M	94	201
13	F	88	197
14	F	56	186
15	M	63	186
16	M	73	178
17	M	91	163
18	M	71	162
19	F	92	162
20	M	83	190
Mean	**NA**	**77.03**	**181.85**

Table 3.2.2 Details about bequeathed individuals sampled for temporal study about the effect of Thiel embalming fluid on epidermal desquamation. First sample was taken pre-embalming, the rest of the samples were taken in weekly intervals. NA = not applicable.

Individual number	Body ID (fingerprint collection purposes)	Sex (M = male, F = female)	Age at death	Number of samples taken per body
21	NA	M	98	5
22	01	F	91	5
23	02	F	90	5
24	NA	F	84	5
25	NA	F	75	5
26	13	F	81	7
27	14	F	77	7
28	17	M	62	5
29	22	F	96	5
30	NA	F	90	5
31	27	F	74	7
32	28	M	74	7
33	29	F	86	7
34	30	F	97	7
35	31	M	62	7
36	32	F	80	7
37	33	F	92	7
38	36	M	79	7
39	37	M	63	7
40	38	M	86	7
Mean	**NA**	**NA**	**81.85**	**NA**

3.2.2 Histological processing

All work concerning tissue collection and processing followed the health and safety rules outlined in university Risk Assessment forms RA/MSI/007 (Dissection of cadavers), RA/MSI/023 (Embedding tissue in wax), RA/MSI/024 (Wax embedded tissue sectioning), RA/MSI/025 (Staining tissue sections with Haematoxylin and Eosin) which were read and signed before the commencement of the study. All the protocols applied to histological sample processing have been previously used in the histological analysis of Thiel-embalmed muscle tissue performed by Tennent (2014).

Following the sample collection, each sample was immersed in 10 ml of 10% neutral-buffered formalin and left in the solution overnight. The samples were

dehydrated by stepwise immersion in ethanol solutions with ascending concentrations according to the protocol included in Table 3.2.3.

Table 3.2.3 Protocol for dehydration of histological samples.

Solution	Time (h)
50% ethanol	1
70% ethanol	1
80% ethanol	1
90% ethanol	1
100% ethanol	1
100% ethanol	1
100% ethanol	overnight

The samples were then transferred into individual glass vials and cleared by 10 ml of xylene (a mixture of isomers) according to the protocol included in Table 3.2.4. The samples were then immersed in molten paraffin and placed in the oven at 60°C for infiltration following the protocol included in Table 3.2.4.

Table 3.2.4 Protocol for histological sample clearing and paraffin infiltration.

Solution	Time (h)
Xylene	1
Xylene	2
Paraffin	1
Paraffin	2
Paraffin	2

The samples were then embedded in fresh paraffin and sectioned using a microtome (Leica, Jung RM2035) with 5 µm thickness of slices. The samples were sectioned until the samples' maximum width (biopsy punch Ø = 4 mm) was exposed. The slices were placed on microscopic slides using a water bath (t = 50°C), air-dried, and then incubated in the oven at 60°C for 2 hours.

The microscopic slides (cooled to room temperature) with adhered samples were stained with haematoxylin and eosin using the protocol included in Table 3.2.5. The samples were stained using a slide holder containing a maximum of 12 slides. The holder with samples was transferred to and from approximately 200 ml of each of the solutions listed in Table 3.2.5. The slides were then cover-slipped using DPX mounting medium, and left to dry in a fume hood overnight.

Table 3.2.5 Protocol for histological sample staining using haematoxylin and eosin.

Solution	Time
Histoclear	3 min
Histoclear	3 min
100% ethanol	3 min
100% ethanol	3 min
70% ethanol	3 min
Tap water	3 min
Mayer haematoxylin	3 min
Tap water	3 min
Scott's tap water	30 s
Tap water	2 min
Eosin	5 min
Tap water	10 s
95% ethanol	15 s
100% ethanol	2 min
100% ethanol	2 min
100% ethanol	2 min
Xylene	3 min
Xylene	3 min

3.2.3 Histological slide observation and definitions of epidermal desquamation

Each histological slide was observed by one observer using optical light microscopy (Leica DM2000) under the magnification of × 400. Histological sections' images were captured using a camera (Leica DFC 295) coupled with the microscope. The full width of the histological sections was visually scanned for the presence of epidermal desquamation. Four types of epidermal desquamation were recorded.

- Partial epidermal desquamation at the level of *stratum lucidum* (SL) was defined as a detachment of more than one cell from other cells within the *stratum lucidum* or *stratum granulosum* (Figure 3.2.2).
- Partial epidermal desquamation at the level of epidermal-dermal junction (EDJ) was defined as a detachment between the epidermal cells of *stratum basale* and dermal papillae observed at more than one dermal papilla (Figure 3.2.2).

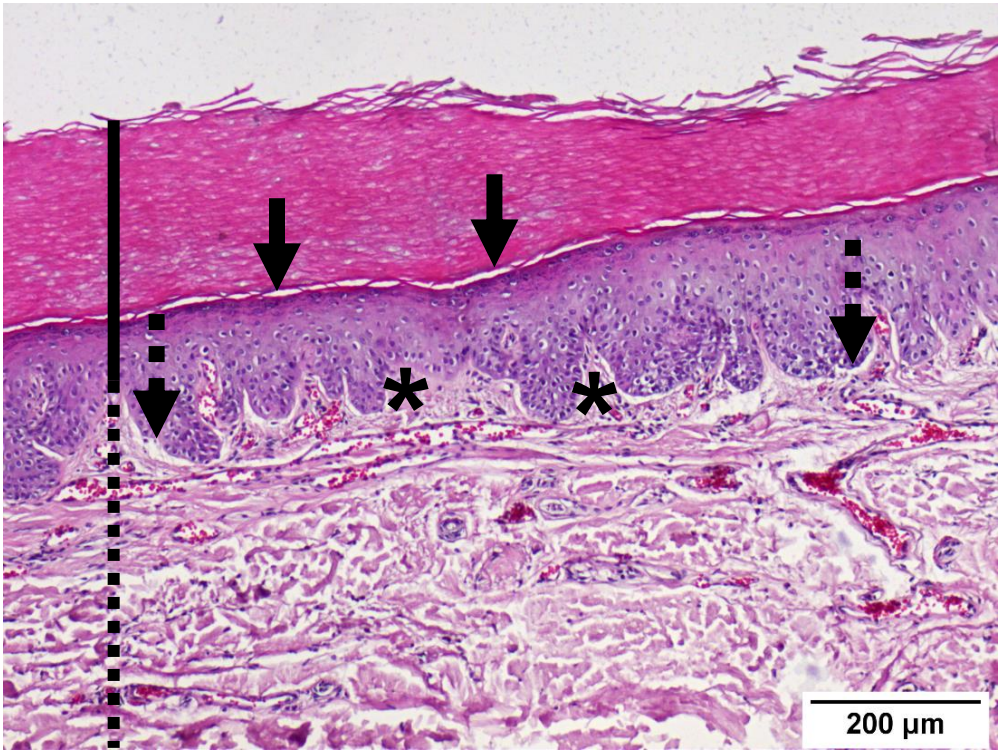

Figure 3.2.2 Micrograph of a histological section of skin sample stained with haematoxylin and eosin showing partial desquamation. Solid line = epidermis, dashed line = dermis, * = examples of dermal papillae. Partial epidermal desquamation at the level of *stratum lucidum* (SL) (solid black arrows) and partial epidermal desquamation at the level of epidermal-dermal junction (EDJ) between *stratum basale* and dermis (black dashed arrows).

If the cellular detachment spanned the approximate length of one cell from the sublayer below, it was not recorded as partial desquamation (Figure 3.2.3A). If the cellular detachment was observed solely at the very ends of the histological section, it was not recorded as partial desquamation due to the possibility of it being caused by mechanical sample manipulation during biopsy excision or embedding (Figure 3.2.3B).

- Complete epidermal desquamation at the level of SL was defined as a complete detachment of *stratum corneum* together with *stratum lucidum* from the *stratum granulosum* of a given histological section (Figure 3.2.4A).
- Complete epidermal desquamation at the level of EDJ was defined as a complete detachment of the epidermis from the dermis (Figure 3.2.4B).

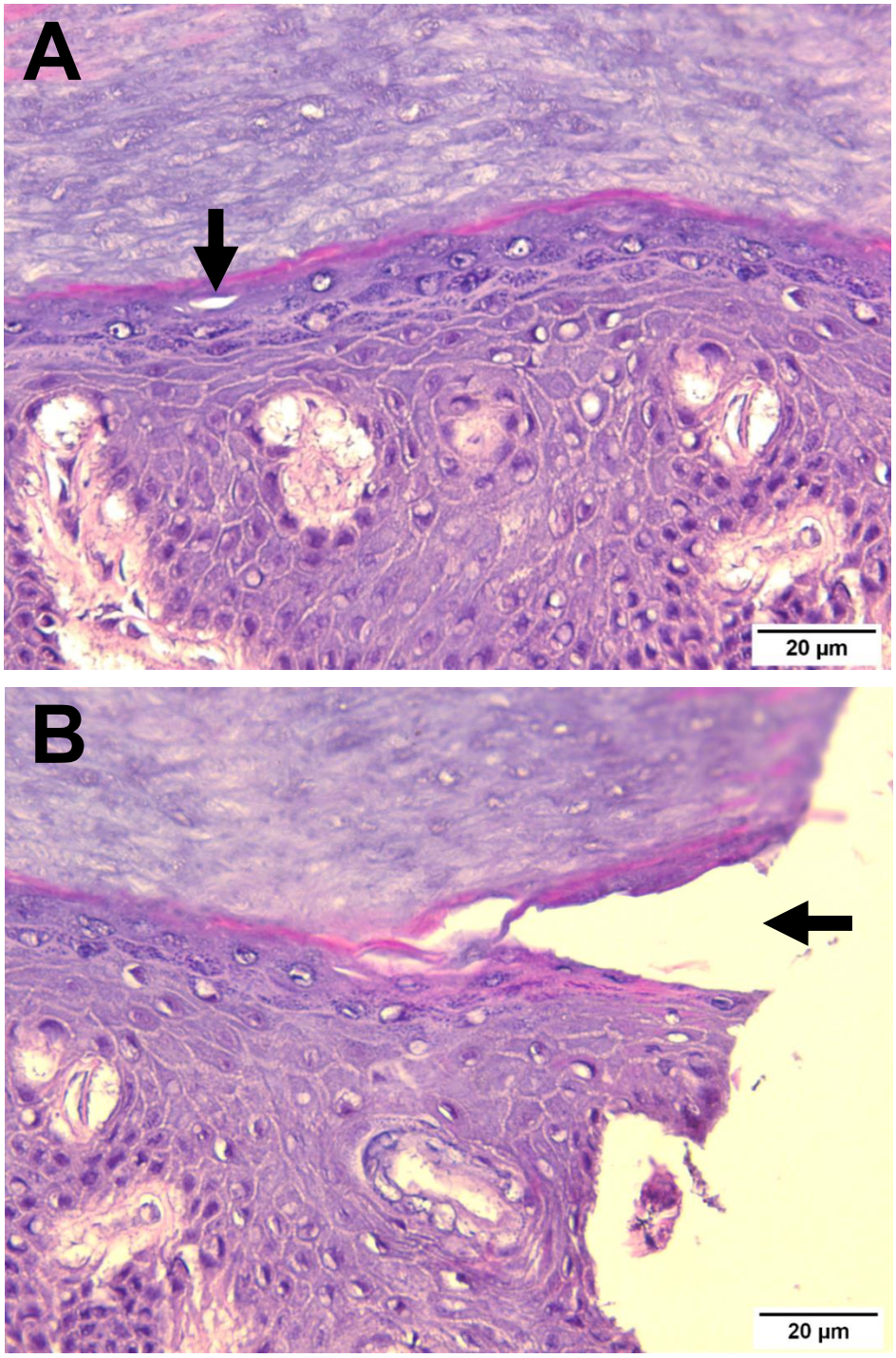

Figure 3.2.3 Micrograph of histological sections of skin sample stained with haematoxylin and eosin showing situations not considered to be partial desquamation. (A) Cellular detachment within epidermal layer (approximately along one cell length) not counted as desquamation at the level of *stratum lucidum* (black arrow). (B) Mechanical separation of epidermal layers at the end of the histological section (black arrow) not counted as desquamation at the level of *stratum lucidum*.

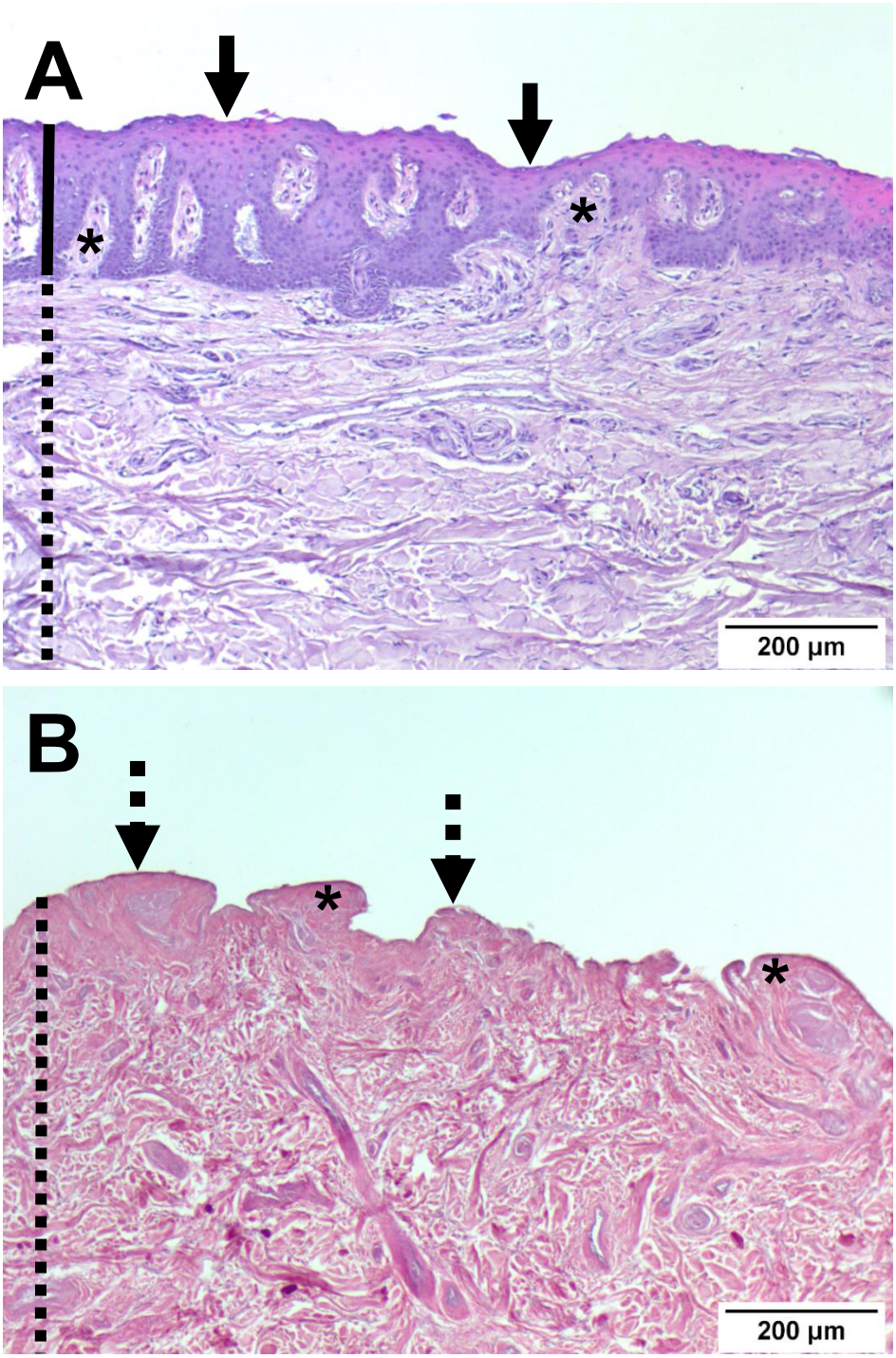

Figure 3.2.4 Micrograph of histological sections of skin sample stained with haematoxylin and eosin showing complete desquamation. Solid line = epidermis, dashed line = dermis, * = examples of dermal papillae. (A) Complete epidermal desquamation at the level of *stratum lucidum* (solid black arrows). (B) Complete epidermal desquamation at the level of epidermal-dermal junction (dashed black arrows).

3.3 Results

3.3.1 Post-embalming controls

Complete epidermal desquamation at the level of the epidermal-dermal junction was observed in all 20 histological sections sampled from bodies after completion of the Thiel embalming process (individuals 1 – 20 included in Table 3.2.1). The bodies sampled post-embalming spent between 23.1 and 36.9 weeks immersed in Thiel embalming fluid. The dermis was exposed in all the histological sections sampled from these post-embalming controls. The dermal papillae were observable in all the histological sections. No remnants of the epidermis were observed in any of the histological sections taken from fully embalmed individuals. Therefore, no observations of *stratum lucidum* and the desquamation process at this skin layer could be made.

3.3.2 Temporal study samples

All four types of epidermal desquamation were observed at some point for the 20 bodies sampled before embalming and then weekly for four and six weeks after commencement of embalming (individuals 21 – 40 included in Table 3.2.2). Figure 3.3.1 illustrates the types of epidermal desquamation occurring in the sample per each week of sampling. There were four types of epidermal desquamation observed – partial and complete epidermal desquamations at the level of *stratum lucidum*, and partial and complete desquamations at the skin level of epidermal-dermal junction.

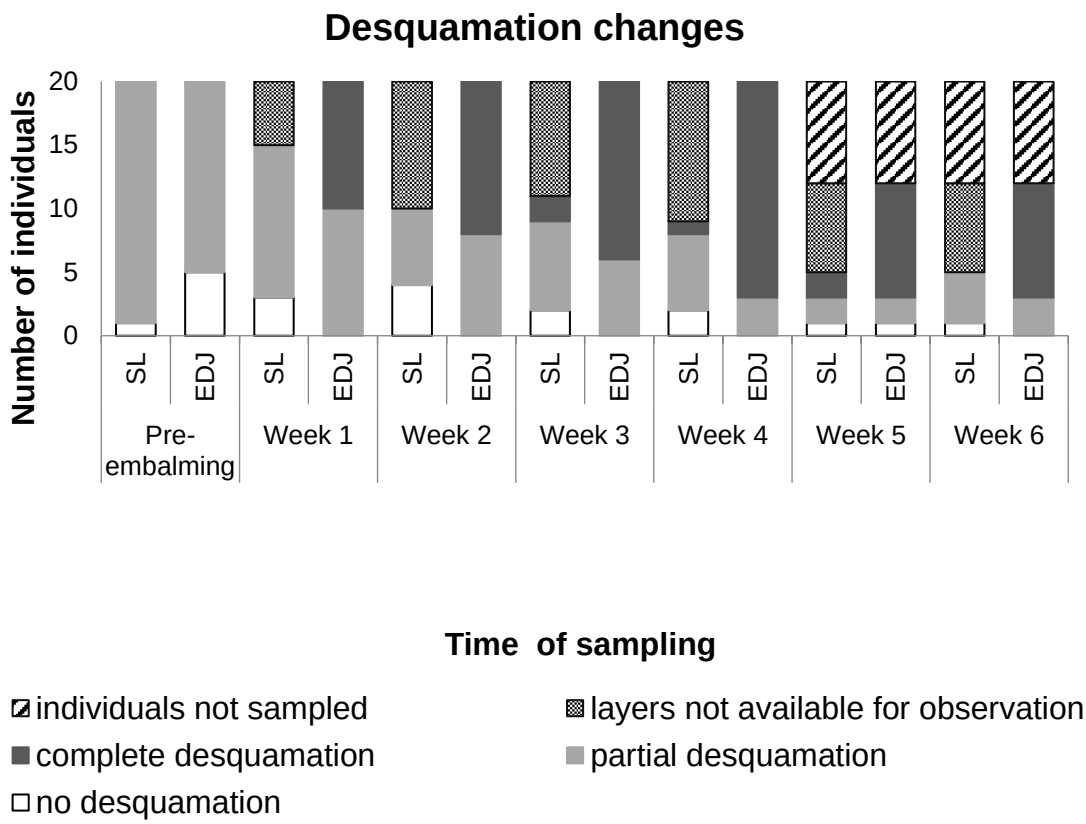

Figure 3.3.1 Types of epidermal desquamation observed in histological sections during different phases of Thiel embalming. SL = epidermal desquamation observed at *stratum lucidum*, EDJ = epidermal desquamation observed at epidermal-dermal junction.

Figure 3.3.2 contains the types of epidermal desquamation observed for each individual.

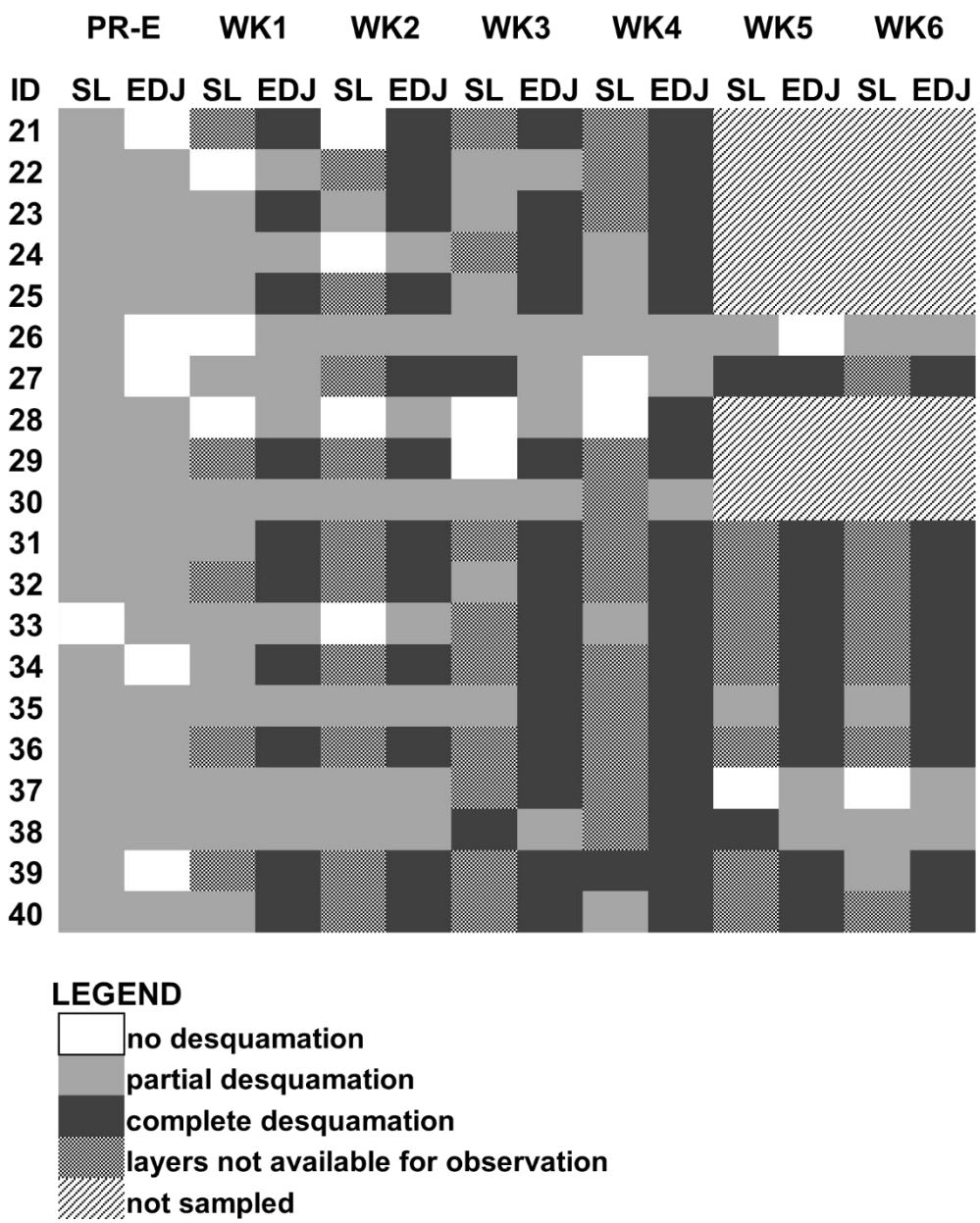

Figure 3.3.2 Types of epidermal desquamation observed in histological sections from individual bodies during different phases of Thiel embalming. SL = skin level of *stratum lucidum*, EDJ = skin level of epidermal-dermal junction, PRE-E = pre-embalming, WK1-6 = week 1 – 6 of immersion in embalming tank.

Both partial and complete epidermal desquamation was observed at the level of *stratum lucidum* during the four- and six-week observations. Partial epidermal desquamation at this level was observed in almost all histological sections sampled before embalming (19 out of 20 bodies), as shown in the pre-embalming column of Figure 3.3.1 and Figure 3.3.2. The number of histological sections with partial epidermal desquamation at the SL skin level decreased after initial immersion in embalming fluid. After the immersion of bodies in Thiel embalming fluid, the upper layers of epidermis became detached and the effect of epidermal

desquamation could not be observed at the SL skin level. Complete epidermal desquamation at the SL skin level was observed in five histological sections (Figure 3.3.2, ID 27, 38, and 39). Complete epidermal desquamation at the SL skin level was observed in histological sections sampled after three, four, and five weeks of the immersion in embalming fluid. Complete lack of any evidence for epidermal desquamation at the SL level was observed in up to four histological sections from each week of sampling.

Both types of epidermal desquamation, partial and complete, were observed at the EDJ level during the four- and six-week observations. Partial epidermal desquamation at the EDJ level was most prevalently observed in histological sections sampled before embalming (15 out of 20 bodies, Figure 3.3.1). The number of histological sections with observed partial epidermal desquamation at this skin level decreased after the immersion in embalming fluid. Complete epidermal desquamation at the EDJ level was observed in half of the histological sections sampled after one week of immersion in embalming fluid (10 out of 20, Figure 3.3.1). Complete epidermal desquamation at the EDJ level was observed in the highest number (17 out of 20) of histological sections sampled after four weeks of immersion in the embalming tank (Figure 3.3.1). There were three bodies in which complete epidermal desquamation at the EDJ observed one week was followed by partial epidermal desquamation at this level in later weeks (Figure 3.3.2, ID 22, 27, 37). There were two bodies without complete epidermal desquamation at the EDJ level in any of the histological sections (Figure 3.3.2; ID 26 and 30). No epidermal desquamation at the level of EDJ was observed in five histological sections sampled before embalming (Figure 3.3.2; ID 21, 26, 27, 34, and 39) and one histological section sampled after five weeks of immersion in embalming fluid (Figure 3.3.2; ID 26).

3.4 Discussion

The results demonstrate that epidermal desquamation in Thiel-embalmed bodies was observed at two histological levels of the epidermis. Epidermal desquamation occurred within or below the *stratum lucidum* and at the epidermal-dermal junction (Figure 3.4.1). Two types of epidermal desquamation (partial or complete) were observed in histological sections at both skin levels. Both types of epidermal desquamation at both levels of the skin occurred at some point prior and during Thiel embalming. For bodies sampled after the completion of embalming (post-embalming controls, ID 1 to 20 in Table 3.2.1) complete epidermal desquamation at the EDJ was observed in all 20 histological sections. For bodies sampled before the embalming and weekly four to six weeks after the immersion in the embalming tank (ID 21 to 40 in Table 3.2.2) partial and complete epidermal desquamation was observed at both skin layers at some point of sampling. Partial epidermal desquamation at both skin levels was the most prevalently observed in histological sections sampled before embalming (19 out of 20 histological sections at the SL skin level, 15 out of 20 histological sections at the EDJ level). Complete epidermal desquamation was not observed in pre-embalming samples at any of the skin layers. Complete epidermal desquamation at the SL skin level was observed in five histological sections exposed to Thiel embalming fluid. Complete epidermal desquamation at the EDJ level was observed in 10 out of 20 histological sections sampled after one week of immersion in Thiel-embalming fluid and 17 out of 20 histological sections sampled after four weeks of immersion in Thiel-embalming fluid.

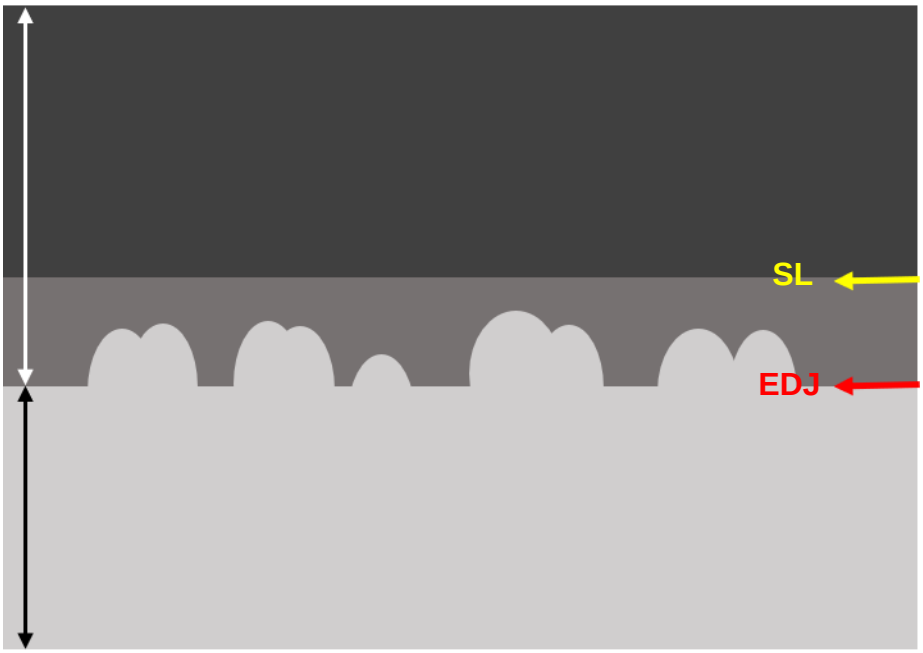

Figure 3.4.1 Schematic of skin highlighting the sites of epidermal desquamation observed in Thiel-embalmed bodies. White double-headed arrow = epidermis, black double-headed arrow = dermis, yellow arrow = site of epidermal desquamation at or below the *stratum lucidum* (SL), red arrow = site of epidermal desquamation at the epidermal-dermal junction (EDJ).

Partial epidermal desquamation at the SL level occurred in pre-embalming samples. The equivalent of partial epidermal desquamation at the SL level defined in this study was also observed in images of non-pathological human thin and thick skin sections (Gudjonsson *et al.*, 2007; Kerr, 2010; Khavkin and Ellis, 2011; Ross and Pawlina, 2016). The images of the mentioned literature describe the skin as normal and containing a detachment of cells occurring within the *stratum corneum* and *stratum lucidum*. The example histological images in literature suggest partial desquamation at this skin level before embalming could be a part of the natural desquamation process; the association with decomposition or histological tissue processing was not ruled out (Kerr, 2010; Khavkin and Ellis, 2011; Ross and Pawlina, 2016). Moreover, the advanced age at death and dry skin of sampled individuals could have an effect on the extent of partial epidermal desquamation at the SL level observed in pre-embalming samples. Hara (1993) opposes this argument, claiming that superficial epidermal desquamation of the topmost skin layer is reduced in elderly individuals due to the larger size of desmosomes in dry skin of elderly people, the reduced turnover of keratinized cells and subsequent thickening of the keratinized epidermal layer. However, according to Elias (1983) and Rawlings (2017), the lamellar lipid

envelope between the *stratum lucidum* and *stratum granulosum* is disorganised and changes structure in dry aged skin, compromising its stability and water non-permeability. The structurally changed lipid layer between the *stratum lucidum* and *stratum granulosum* occurring in dry aged skin could be an explanation of observed partial epidermal desquamation in the pre-embalmed histological sections of the current study.

Partial epidermal desquamation was observed at the EDJ skin level in 15 out of 20 histological sections before Thiel embalming; the rest of the histological sections showed no epidermal desquamation at this skin layer. Clark *et al.* (2006) claim that loosening of the epidermis from the dermis can be visible from up to 48 hours after death. Clark *et al.* (2006) call this process skin slippage and explain the separation of the skin layers as a release of hydrolytic enzymes by cells at the epidermis-dermis junction. There was an interval of one to five days between the death of the individuals and their subsequent embalming and therefore the recovery of skin samples before embalming. Based on observations of Clark *et al.* (2006), the individuals with no observed partial epidermal desquamation at the EDJ would be expected to have an interval between death and embalming which was shorter than two days. However, histological sections in which no epidermal desquamation at the EDJ was observed came from individuals with one, three, or four-day intervals between death and embalming. Other factors such as environmental and individual differences could influence epidermal desquamation at the EDJ skin level before embalming. Temperature is an example of environmental factors affecting the performance of autolytic enzymes during body decomposition (Gill-King, 2006); the enzymes decrease their activity with decreasing temperature and concomitant body decomposition rate decreases. Therefore, in cases of bodies being stored in a refrigerator or freezer for the interval between death and embalming, the autolysis of EDJ could be hampered. Unfortunately, no information about the storage (refrigerator or freezer, time of the storage) of the bodies for the interval between death and embalming was available to us. Furthermore, an individual's pathologies, occupation, and age can all have an influence on the structure and function of the EDJ and could affect partial epidermal desquamation before embalming (Montagna and Carlisle, 1979; Langton *et al.*, 2016).

In some histological sections, partial epidermal desquamation at the SL skin level was observed in the pre-embalming histological sections, but no epidermal desquamation at this skin level was observed in histological sections sampled from the same bodies after the immersion in Thiel embalming fluid. It is theorised that this adherence within the SL skin layer after the exposure to Thiel embalming fluid could be an effect of the fixative chemical components within the embalming solution. However, the exact biochemical processes and chemical components involved in possible adherence of the skin layers remain to be investigated. Research to date has focused only on the biochemical effects of Thiel embalming fluid on muscular proteins and collagen (Benkhadra *et al.*, 2012; Tennent, 2014; McDougall *et al.*, 2019). It is also important to mention that the number of histological sections containing upper epidermal layers was reduced by the increasing occurrence of complete epidermal desquamation at the EDJ (macroscopic loss of epidermis before sampling). Therefore, the adherence within the keratinized layers of the epidermis after the immersion in Thiel embalming fluid was not observable in all histological samples. Likewise, the extent of partial epidermal desquamation at the SL layer could not be assessed in all histological sections.

Complete epidermal desquamation at the SL skin level was observed in five histological sections (present in three bodies out of 20). This type of epidermal desquamation was coupled with partial epidermal desquamation at the EDJ in cases of three histological sections (two bodies, ID numbers 27 and 38 in Figure 3.3.2). Such complete epidermal desquamation at SL in Thiel-embalmed bodies was observed and reported only by Boaz (n.d.) who did not state the number of cases in which such desquamation was observed, nor did he state whether there was any epidermal desquamation observed at the EDJ. In two histological sections (ID numbers 27 and 39 in Figure 3.3.2), complete epidermal desquamation at the SL level coupled with complete epidermal desquamation at the EDJ was observed. Although the prevalence of complete epidermal desquamation at the SL skin level appears to be low, it is impossible to state the exact number of cases with such epidermal desquamation due to macroscopic loss of the epidermis before sampling took place (associated with complete desquamation at the EDJ).

Complete epidermal desquamation at the EDJ was observed in at least one histological section sampled from 38 (out of 40) Thiel-embalmed bodies. Complete epidermal desquamation at this skin level was observed in all 20 histological sections sampled from fully embalmed bodies. There is no literature to date explaining which chemical component from Thiel embalming solution is involved in the detachment at the epidermal-dermal junction on the microscopic level. McDougall *et al.* (2019) report that boric acid and probably other components of Thiel embalming solution are responsible for damage to skeletal muscle and tendon internal tissue structure. Further research is needed to establish whether any component of Thiel embalming fluid chemically contributes to complete epidermal desquamation at the EDJ or whether the solution does not affect the skin slippage process described by Clark *et al.* (2006). As already mentioned in section 2.6.2 of the literature review, cases of complete epidermal desquamation at EDJ and exposed dermis due to decomposition processes in un-embalmed bodies are known to occur by fingerprint collection and analysis experts (Okajima, 1979, 1984; Mizokami *et al.*, 2015). Epidermal desquamation in Thiel-embalmed bodies may also be influenced by mechanisms other than at the chemical level. There is mechanical manipulation when handling the embalming or embalmed bodies causing potential detachment of skin layers (Eisma *et al.*, 2013). After the body is taken out of the tank where they are being embalmed (i.e. fully embalmed), the bodies are manually ‘scrubbed’ (the loosened epidermis is manually detached and removed if still attached to the body, only the epidermis which is loose and fully detached is removed) as a part of the body preparation process for further use in dissection or other courses. The body preparation process, therefore, contributes to the observed complete epidermal desquamation in all 20 fully embalmed bodies (post-embalming controls) and is a potential limitation when studying temporal changes in skin characteristics as a result of contact with Thiel embalming solution.

The fact that epidermal desquamation was observed in two sublayers of the skin in the bodies embalmed using Thiel embalming fluid may have an impact on the appearance of fingerprints collected from these bodies after the desquamation occurred (Figure 3.4.2). If the desquamation occurred at the SL skin level, the fingerprint taken from the remaining layers of skin after the desquamation would most likely copy the appearance of a ‘classic’ epidermal surface fingerprint.

Whereas the fingerprint collected from the dermal layer after epidermal desquamation at the EDJ would have an appearance of complex double rows of papillae (Plotnick and Pinkus, 1958; Okajima, 1984). Moreover, in younger sub-adult individuals the exposed dermis could have yet another appearance because the papillae have a less structured appearance and their relative position under the epidermal ridges can differ, as suggested by Chacko and Vaidya (1968) and Okajima (1975). However, in cases of bequeathed bodies, the scenario with subadult bodies would be less likely to occur and would not occur for individuals below the age of 12 years (Scottish Government, 2019).

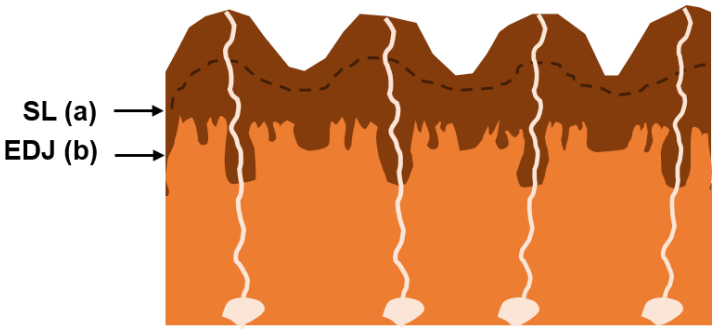

Figure 3.4.2 Schematic of friction ridge skin cross-section. SL (a) indicates where epidermal desquamation occurs within or below the keratinised skin layer. EDJ (b) indicates where epidermal desquamation occurs between the epidermis and dermis.

The timeframe of complete epidermal desquamation at the EDJ in Thiel-embalmed bodies varies. This type of epidermal desquamation was observed in half of the histological sections sampled during the first week of immersion in Thiel embalming fluid. However, complete epidermal desquamation at the EDJ was not observed in two bodies sampled for the duration of the first four and six weeks of immersion in Thiel embalming fluid (ID numbers 30 and 26 in Figure 3.3.2, respectively). Research studies of skin changes and decomposition in the water suggest the separation of the epidermal layer occurs more rapidly after contact with the water (Weber, 1982; Reh, 1984; Weber and Laufkötter, 1984; Pueschel and Schneider, 1985). According to Weber and Laufkötter (1984), the separation of keratinised skin layer (corresponding to the partial epidermal desquamation at the SL layer in this study) occurs around 10 hours after the immersion in the water. The study of Schneider and Pueschel (1985) suggests that epidermal desquamation between the epidermis and dermis occurs between 18 to 48 hours after immersion in the water, depending on the water temperature

and salinity. Therefore, more frequent sampling of bodies immersed in Thiel embalming fluid would be suggested within the first 10 to 48 hours of immersion.

As previously mentioned, thinning, straightening of EDJ and subsequent skin fragility are the result of aged skin undergoing intrinsic biochemical changes as well as changes due to extrinsic factors (photo-ageing, manual work) (Montagna and Carlisle, 1979; Khavkin and Ellis, 2011; Langton *et al.*, 2016). The amount of generic shearing force and friction applied to the thick skin on thumbs combined with the old age of bequeathed individuals will most likely have an effect on the timeframe of complete epidermal desquamation at the EDJ. However, this claim is unsupported by data, as no information about the occupation of bequeathed individuals is available. Lastly, the quality of hand vascular structures could have an effect on the timeframe of Thiel-induced epidermal desquamation at the EDJ. The initial perfusion of a body by Thiel embalming fluid is dependent on the state of veins and arteries (Ottone *et al.*, 2016). If the vasculature of hands is poor, perfusion fluid might not reach the hands and digits properly, interfering with the quality of embalming in the hands (Kerckaert *et al.*, 2008; Eisma *et al.*, 2013; Kocbek and Rakusa, 2017). Drying of the tissues in hands could subsequently have an effect on epidermal desquamation at any skin level. However, a larger sample size will be needed to confirm the trends observed in epidermal desquamation in Thiel-embalmed bodies.

Further studies could benefit from investigating epidermal desquamation in Thiel-embalmed bodies of wider age-range variety, as it was mentioned the dermis characteristics change with the age of individuals which can affect the timeframe and nature of epidermal desquamation (Chacko and Vaidya, 1968; Okajima, 1975; Misumi and Akiyoshi, 1984). However, it needs to be noted that age is a factor that cannot be influenced when working with bequeathed bodies since most bequeathals are from older individuals. Further studies would also benefit from a change in the sampling strategy. More frequent sampling during the first week of body-immersion in embalming tanks could provide more detailed information on the extent of desquamation occurring at the SL and EDJ. Future research could also explore skin samples taken weekly from the bodies throughout the full time during which the body is immersed in an embalming tank (approximately six months). Furthermore, choosing a larger distance between

sampling spots within areas of friction ridge skin could minimise forces interfering with the skin chosen for further sampling. Another avenue to explore could be taking extra skin samples before embalming and following the epidermal desquamation timeframe in fresh and marine water environments to obtain timeframes comparable to Thiel-embalmed skin samples.

In conclusion, epidermal desquamation was observed in thick skin histological sections sampled from Thiel-embalmed bodies at two levels: *stratum lucidum* and epidermal-dermal junction. Two types of epidermal desquamation were observed, partial and complete, at the two skin levels. Partial epidermal desquamation was observed at both skin levels in most histological sections sampled before embalming. Complete epidermal desquamation at the EDJ was observed more frequently than complete epidermal desquamation at the SL skin level in histological sections sampled from Thiel-immersed bodies. Individual variation in the timeframe of epidermal desquamation at the EDJ level was observed, but complete epidermal desquamation at the EDJ was observed in half of the histological sections sampled after the first week of immersion in Thiel embalming fluid. Since complete epidermal desquamation at the EDJ exposed the dermis in thick friction ridge skin, the Thiel-embalmed bodies could be used for the study and comparison of dermal and epidermal fingerprints.

Chapter 4 Comparison of epidermal and dermal fingerprints in Thiel-embalmed elderly individuals

4.1 Introduction

As was shown in section 2.6.2 of the literature review, a limited amount of research has been undertaken on the comparison between epidermal and dermal fingerprints (Plotnick and Pinkus, 1958; Principe and Verbeke, 1973; Okajima, 1984; Mizokami *et al.*, 2015; Khoo *et al.*, 2016). Where it has been undertaken, the research involved a limited number of subjects and in some studies, there was a lack of data such as age at death of subjects which is an important factor when collecting and comparing epidermal and dermal fingerprints (Plotnick and Pinkus, 1958; Chacko and Vaidya, 1968). The majority of the studies mention the need for the removal of digits from bodies as part of their method of dermal skin layer exposure and analysis (Okajima, 1984; Mizokami *et al.*, 2015). Such practices do not align with standard operating procedures of UK body identification practices and are considered unethical and dangerous as they can introduce possible mistakes in identification or repatriation (Black *et al.*, 2010; National Crime Agency, 2010).

The previous chapter showed that the dermal layer is exposed in Thiel-embalmed bodies during embalming. This offers an opportunity for the collection of epidermal and dermal fingerprint sets from the same individuals without the need for any further chemical treatment of epidermis and/or removal of digits from the hand of the individuals for research purposes. The process of embalming with Thiel does pose other challenges, such as the oily nature of Thiel embalming fluid consistently seeping through the skin pores which may introduce smudging and smearing of fingerprints upon lifting and hamper photographic capture of the full friction ridge surface due to light reflection. Furthermore, the fact that the bequeathed are often of advanced age may have adverse effects on the quality of friction ridges (Misumi and Akiyoshi, 1984). Nevertheless, this study explores the possibilities of epidermal-dermal fingerprint collection and comparison from Thiel-embalmed bodies and reports on their potential to serve as a suitable model for further research of dermal fingerprint collection and analysis.

4.1.1 Aims

This study aims to examine the quality, usability, and comparability of epidermal and dermal fingerprints collected from Thiel-embalmed bodies. The purpose of the first aim is to establish whether dermal and epidermal fingerprints collected from Thiel-embalmed bodies could be used as a model for any potential future research and training in identification of unidentified bodies. The second aim of the study is to compare which fingerprint collection technique – granular black powder or digital photography – would be more suitable to collect higher quality epidermal and dermal fingerprints from Thiel-embalmed bodies. The third aim of the study is to collect materials for creation of a ground truth database of epidermal and dermal fingerprints that could be used as a training resource for fingerprint examiners and also for any future research in the field of identification of the deceased and disaster victim identification.

4.1.2 Terminology

To maintain the brevity of the text and consistency in the terminology used throughout this and following chapters, any images of digits with friction ridge skin will be termed as ‘fingerprints collected using photography’ even though the images do not contain any impressions of the friction ridges. Therefore, fingerprints collected using powder and images of digits with friction ridge skin will be all classified as fingerprints.

Furthermore, to clarify terminology used in connection to the fingerprint quality and usability assessment, the term quality is used in the context of overall friction ridge quality defined in Hicklin *et al.* (2011) as a measure of the usefulness and difficulty anticipated in performing a comparison using the entire friction ridge impression (i.e. clarity of fingerprint). However, the term quality in the case of this thesis is not defining solely the clarity of fingerprints as was done in the study of Hicklin *et al.* (2011); the term also includes certain features of fingerprint usability or sufficiency assessment. Fingerprint usability used in the thesis could be then interpreted as a measure of fingerprint sufficiency, suitability, or value similar to terms used by Neumann *et al.* (2013) and Ulery *et al.* (2013), defined as fingerprint examiner’s determination if the fingerprint has sufficient information to make a comparison. Whereas the term quality was suggested by the Scottish

fingerprint examiners upon initial conversations during the project design (personal communication, B. Robertson 2018), the term usability was added by the author of the thesis at the later stage of the project in order to find a measure applicable to fingerprint assessments performed by experts from all countries participating in the study.

4.2 Materials and Methods

4.2.1 Fingerprint collection

4.2.1.1 Donors

Fingerprints were taken from 67 bodies bequeathed to the Centre for Anatomy and Human Identification at the University of Dundee. The population used in the current study was of European white origin, for the information on sex and age at death see Table 4.2.1. Only individuals who have consented to the photography of their body/body parts were included in this study. All procedures performed in the study followed appropriate Scottish legislation [the Anatomy Act 1984 and the Human Tissue (Scotland) Act 2006] and no specific ethical approval was required for fingerprint collection from the bodies (Appendix 1).

Table 4.2.1 Sex and age at death of bequeathed individuals used for fingerprint collection.

Number	Females		Males	
	Body ID	Age at death	Body ID	Age at death
1	01	91	03	96
2	02	91	05	93
3	04	92	06	77
4	07	83	08	77
5	09	90	12	69
6	10	81	17	62
7	11	82	23	50
8	13	81	24	64
9	14	77	25	71
10	15	91	28	74
11	16	88	31	62
12	18	65	34	85
13	19	92	35	71
14	20	77	36	79
15	21	94	37	63
16	22	96	38	86
17	26	80	39	89
18	27	86	47	83
19	29	86	48	81
20	30	97	50	88
21	32	80	51	80
22	33	92	52	69
23	40	88	53	85
24	41	74	54	80
25	42	68	55	43
26	43	73	56	67
27	44	81	57	92
28	45	90	58	78
29	46	77	59	91
30	49	92	63	76
31	60	54	66	70
32	61	67	67	80
33	62	82	-	-
34	64	80	-	-
35	65	55	-	-
Average	-	**82.09**	**-**	**75.97**

4.2.1.2 Procedure

All work concerning the collection of epidermal and dermal fingerprints from Thiel-embalmed bodies followed the health and safety rules outlined in university Risk Assessment forms RA/MSI/039 (Fingerprint collection from cadavers) and RA/MSI/010 (Image taking), and Standard Operating Procedures SOP/MSI/037 (Fingerprint collection from cadavers), which were read and signed before the commencement of the study. Table 4.2.2 and Table 4.2.3 contain the number of collected epidermal fingerprints from each body and collection techniques employed. The list of all individual fingerprints collected can be found in electronic format on a compact disc (shared online depository) as supplementary material

(Appendix 2). For the first four bodies, epidermal fingerprints were collected before and after the initial perfusion of bodies with Thiel embalming fluid. Based on the quality of collected epidermal fingerprints from the first four bodies, the collection of fingerprints in the further 63 bodies was performed after the initial perfusion of the body with Thiel embalming fluid. After the initial perfusion, the fingertips became inflated and the skin creases were smoothened to an extent allowing for the collection of fingerprints with a greater amount of ridge detail. Furthermore, perfusion with Thiel embalming fluid and the time the bodies spent at room temperature (approximately between 30 minutes and 2 hours) partially loosened muscles affected by rigor mortis and/or by body storage conditions (freezer/refrigerator) before the start of perfusion. The time the body spent at room temperature and perfusion itself partially unstiffened joints making the manipulation of the upper limbs and digits easier.

Table 4.2.2 Number of epidermal fingerprints collected from the first 20 bodies. L = left hand, R = right hand.

Body ID	Photo (Micro-camera)															Powder							Grand total
	Pre-perfusion							Post-perfusion							Total	Pre-perfusion			Post-perfusion			Total	
	Pre-powder			Post-powder			Total	Pre-powder			Post-powder			Total									
	L	R	total	L	R	total		L	R	total	L	R	total			L	R	total	L	R	total		
1	4	4	8	4	4	8	16	-	-	-	-	-	-	-	16	4	5	9	4	-	4	13	29
2	4	4	8	4	4	8	16	-	-	-	-	4	4	4	20	5	5	10	-	5	5	15	35
3	4	4	8	4	4	8	16	-	4	4	-	4	4	8	24	5	5	10	-	5	5	15	39
4	4	3	7	4	4	8	15	-	4	4	-	4	4	8	23	5	5	10	-	5	5	15	38
5	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
6	-	-	-	-	-	-	-	4	4	8	4	-	4	12	12	-	-	-	5	5	10	10	22
7	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
8	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
9	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
10	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
11	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
12	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
13	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	4	5	9	9	25
14	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	4	5	9	9	25
15	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
16	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
17	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	4	5	9	9	25
18	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
19	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
20	-	-	-	-	-	-	-	4	4	8	4	4	8	16	16	-	-	-	5	5	10	10	26
Total	**16**	**15**	**31**	**16**	**16**	**32**	**63**	**64**	**72**	**136**	**64**	**72**	**136**	**272**	**335**	**19**	**20**	**39**	**81**	**95**	**176**	**215**	**550**

Table 4.2.3 Number of epidermal fingerprints collected from the next 47 bodies. L = left hand, R = right hand.

Body ID	Photo (Camera)							Powder			Grand Total
	Pre-powder			Post-powder			Total				
	L	R	total	L	R	total		L	R	total	
21	4	4	8	4	4	8	16	5	5	10	26
22	4	4	8	4	4	8	16	4	5	9	25
23	4	4	8	4	4	8	16	5	5	10	26
24	4	4	8	4	4	8	16	5	5	10	26
25	4	4	8	4	4	8	16	5	5	10	26
26	4	4	8	4	4	8	16	5	5	10	26
27	4	4	8	4	4	8	16	5	5	10	26
28	4	4	8	4	4	8	16	4	5	9	25
29	4	4	8	4	4	8	16	4	5	9	25
30	4	4	8	4	4	8	16	4	5	9	25
31	4	4	8	4	4	8	16	4	5	9	25
32	4	4	8	4	4	8	16	4	5	9	25
33	4	4	8	4	4	8	16	4	5	9	25
34	4	4	8	4	4	8	16	5	5	10	26
35	4	4	8	4	4	8	16	5	5	10	26
36	4	4	8	4	4	8	16	4	5	9	25
37	4	4	8	4	4	8	16	4	5	9	25
38	4	4	8	4	4	8	16	4	5	9	25
39 - 67	4	4	8	4	4	8	16	5	5	10	26
Total	**188**	**188**	**376**	**188**	**188**	**376**	**752**	**225**	**235**	**460**	**1212**

For the collection of epidermal fingerprints from the first 20 bodies, a strapping mechanism was used to secure the hand and digits (Figure 4.2.1). The forearm, wrist, palm, and digits were securely strapped with cable ties on a surgical lead hand. After a discussion with a highly experienced scene of crime officer, the use of the surgical lead hand was discontinued due to the interference of cable ties with friction ridge skin. The efficiency of the surgical lead hand in the straightening of the digits was also limited. Holding the digits straight manually proved to be more efficient albeit it required more practice in synchronisation with imaging.

Before fingerprint collection, the hands were moisturised with a heavy-duty oil-free moisturiser (Corn Huskers) to hydrate the dry skin and smoothen any creases in the friction ridge skin. After the surface was dried with a paper towel, the fingertips of the second to fifth digits were photographed separately using a digital micro-camera (Dino-Lite Digital Microscope, AM3113T) in the case of the epidermal fingerprints collected from the initial 20 bodies (550 fingerprints) and a digital camera (Olympus, TG-5) attached to a gorilla tripod for the remaining 47 bodies (1212 fingerprints) (Table 4.2.2 and Table 4.2.3), as demonstrated in Figure 4.2.2. The thumb was excluded from the collection using photography, due to its position which required a different angle under which photography

needed to be taken. The camera was focused on the central area of the fingertip to capture the core pattern of the friction ridges.

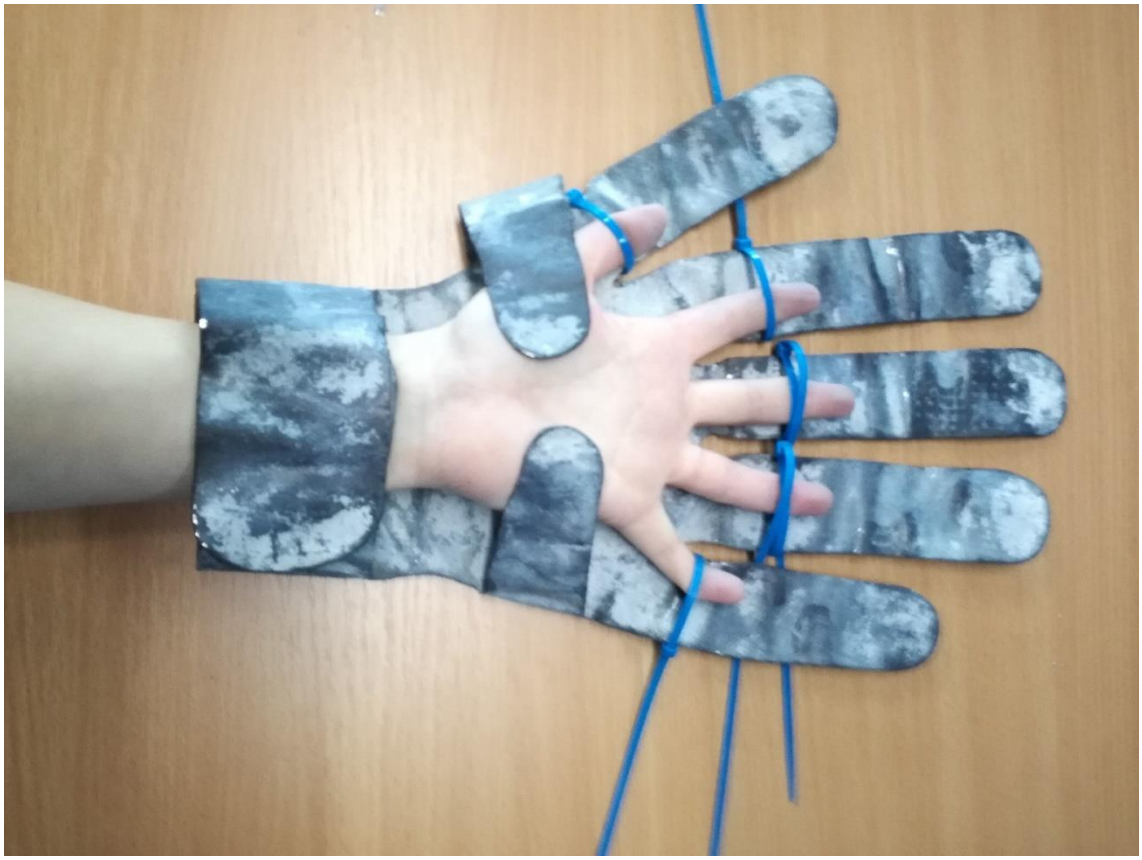

Figure 4.2.1 Photograph of a strapping mechanism showing surgical lead hand and cable ties tested on living individual.

Figure 4.2.2 Photograph of experimental setup for imaging of digits using digital camera.

After images were taken, a fine layer of granular black fingerprinting powder was applied on the surface of each fingertip using a squirrel-hair brush. Fingerprints were lifted using white adhesive address labels which were then attached to an acetate sheet. The fingertips of digits 2 – 5 were then photographed again with residual powder remaining on the surface of the skin to provide different contrast

conditions. The whole procedure was repeated with the second hand. Fingerprints were not collected in cases where digits were in a flexed position and could not be straightened without invasive procedure (sectioning of muscle tendons or opening joint capsules). Fingerprints were also not collected if the digit had been used for histological sampling (for further details see section 3.2.1, Table 3.2.2).

A dermal set of fingerprints was collected in the same way around the time of or after the completion of embalming, approximately 6 months after the initial perfusion with Thiel embalming fluid, during which time the body will have been immersed in Thiel embalming fluid. Table 4.2.4 contains the time each body spent in an immersion tank filled with Thiel embalming fluid. In some cases, there was a time interval between the completion of embalming and dermal fingerprint collection due to the availability of the mortuary and the author; these times are also included in Table 4.2.4. When dermal prints were recovered, the hand was dried using a paper towel. Due to the oily nature of Thiel embalming fluid seeping through the sweat pores on the surface of the skin, each fingertip was dried using a paper towel, de-greased by pouring a small amount of petrol lighter fluid (Ronson) over the digit which was again wiped dry with a paper towel. The procedures of de-greasing, powder application, and lifting were repeated for each digit separately and in quick succession to limit the seepage of Thiel embalming fluid. Also, care was taken to only exert a very small amount of pressure when applying the adhesive address labels onto the powdered dermal skin surface to limit the deformation of dermal papillae and distortion of fingerprint due to the oily surface. The collection of dermal powder fingerprints was repeated until the author judged it to be of the best possible quality.

Table 4.2.4 Number of dermal fingerprints collected from all bodies. L = left hand, R = right hand, NA = not applicable.

Body ID	Photo (Camera)							Powder			Grand Total	Days between collections	Days body spent in embalming tank	Days between dermal collection and embalming completion
	PRE-powder			POST-powder			Total							
	L	R	total	L	R	total		L	R	total				
01	4	4	8	4	4	8	16	4	4	8	24	175	205	+30
02	4	4	8	4	4	8	16	4	5	9	25	272	204	-68
03	4	4	8	4	4	8	16	5	5	10	26	333	243	-90
04	4	4	8	4	4	8	16	5	5	10	26	333	266	-67
05	4	4	8	4	4	8	16	5	5	10	26	245	251	+6
06	4	4	8	4	4	8	16	5	5	10	26	142	243	+101
07	4	4	8	4	4	8	16	5	5	10	26	235	238	+3
08	4	4	8	4	3	7	15	5	5	10	25	138	241	+103
09	4	4	8	-	4	4	12	5	5	10	22	219	224	+5
10	4	4	8	4	4	8	16	5	5	10	26	378	315	-63
11	4	4	8	4	4	8	16	5	5	10	26	371	301	-70
12	-	4	4	4	4	8	12	5	5	10	22	210	208	-2
13	4	4	8	4	4	8	16	4	5	9	25	349	252	-97
14	4	4	8	4	4	8	16	4	5	9	25	191	194	+3
15	4	4	8	4	4	8	16	5	5	10	26	186	186	0
16	4	4	8	4	4	8	16	5	5	10	26	341	258	-83
17	4	4	8	4	4	8	16	4	5	9	25	176	179	+3
18	4	4	8	4	4	8	16	5	5	10	26	322	239	-83
19	4	4	8	4	4	8	16	5	5	10	26	317	232	-85
20	4	4	8	4	4	8	16	5	5	10	26	315	243	-72
21	4	4	8	4	4	8	16	5	5	10	26	261	188	-73
22	4	4	8	4	4	8	16	4	5	9	25	245	190	-55
23	4	-	4	4	-	4	8	5	-	5	13	235	180	-55
24	4	4	8	4	4	8	16	5	5	10	26	228	175	-53

The table continues on the following page.

Continuation of Table 4.2.4.

Body ID	Photo (Camera)							Powder			Grand Total	Days between collections	Days body spent in embalming tank	Days between dermal collection and embalming completion
	PRE-powder			POST-powder			Total							
	L	R	total	L	R	total		L	R	total				
25	-	4	4	-	4	4	8	-	4	4	12	229	181	-48
26	-	4	4	-	4	4	8	-	5	5	13	221	185	-36
27	4	4	8	4	4	8	16	4	5	9	25	196	174	-22
28	4	4	8	4	4	8	16	4	5	9	25	198	176	-22
29	4	4	8	4	4	8	16	4	5	9	25	192	175	-17
30	4	4	8	4	4	8	16	4	5	9	25	191	177	-14
31	4	2	6	4	2	6	12	4	4	8	20	180	180	0
32	4	4	8	4	4	8	16	4	5	9	25	176	176	0
33	4	4	8	4	4	8	16	4	5	9	25	176	176	0
34	4	4	8	4	4	8	16	5	5	10	26	179	179	0
35	4	4	8	4	4	8	16	5	5	10	26	195	195	0
36	4	-	4	4	-	4	8	4	-	4	12	189	189	0
37	4	4	8	4	4	8	16	4	5	9	25	186	186	0
38	4	4	8	4	4	8	16	4	5	9	25	191	190	-1
39	4	4	8	4	4	8	16	5	5	10	26	193	193	0
40	4	4	8	4	4	8	16	5	5	10	26	182	182	0
41	4	4	8	4	4	8	16	5	5	10	26	183	183	0
42	4	4	8	4	4	8	16	5	5	10	26	183	183	0
43	4	4	8	4	4	8	16	5	5	10	26	177	180	+3
44	4	4	8	4	4	8	16	5	5	10	26	224	194	-30
45	4	4	8	4	4	8	16	5	5	10	26	218	197	-21
46	4	4	8	4	4	8	16	5	5	10	26	217	197	-20
47	4	4	8	4	4	8	16	5	5	10	26	217	196	-21
48	3	4	7	4	4	8	15	5	5	10	25	216	202	-14

The table continues on the following page.

Continuation of Table 4.2.4.

Body ID	Photo (Camera)							Powder			Grand Total	Days between collections	Days body spent in embalming tank	Days between dermal collection and embalming completion
	PRE-powder			POST-powder			Total							
	L	R	total	L	R	total		L	R	total				
49	4	4	8	4	4	8	16	5	5	10	26	190	190	0
50	4	4	8	4	4	8	16	5	5	10	26	195	190	-5
51	4	4	8	4	4	8	16	5	5	10	26	195	191	-4
52	4	4	8	4	4	8	16	5	5	10	26	194	195	+1
53	4	4	8	4	4	8	16	5	5	10	26	194	195	+1
54	3	3	6	3	3	6	12	3	3	6	18	214	215	+1
55	4	4	8	4	4	8	16	5	5	10	26	210	203	-7
56	4	4	8	4	4	8	16	5	5	10	26	211	219	+8
57	-	4	4	-	4	4	8	-	5	5	13	188	188	0
58	4	4	8	4	4	8	16	5	5	10	26	209	252	+43
59	4	4	8	4	4	8	16	5	5	10	26	187	187	0
60	4	5	9	4	5	9	18	5	5	10	28	176	240	+64
61	4	4	8	4	4	8	16	5	5	10	26	175	175	0
62	4	4	8	4	4	8	16	5	5	10	26	195	203	+8
63	4	4	8	4	4	8	16	5	5	10	26	183	202	+19
64	4	4	8	4	4	8	16	5	5	10	26	191	208	+17
65	4	2	6	4	2	6	12	5	2	7	19	183	194	+11
66	4	4	8	4	4	8	16	5	5	10	26	172	189	+17
67	4	4	8	4	4	8	16	5	5	10	26	169	187	+18
Total	**250**	**256**	**506**	**251**	**255**	**506**	**1012**	**302**	**317**	**619**	**1631**	**NA**	**NA**	**NA**

4.2.2 Baseline fingerprint assessment

4.2.2.1 Sample

The total sample consisted of epidermal and dermal fingerprints (n = 3393) collected using black powder and photography. In total there were 1762 fingerprints collected from the epidermal layer and 1631 fingerprints collected from the dermal layer (Table 4.2.2, Table 4.2.3, Table 4.2.4). The difference in the number of dermal fingerprints collected when compared to epidermal fingerprints is caused by numerous issues. There was a lack of epidermal desquamation in 8 individuals (numbers 23, 25, 26, 31, 36, 54, 57, and 65) in the area of hands and digits despite the completion of the embalming process (approximately 6 months). Individual 6 is missing some photographs of epidermal fingerprints due to the position of hand and digits which could not be straightened prior to full immersion in Thiel fluid. Furthermore, the first four bodies sampled for epidermal fingerprints had more fingerprints collected in comparison to dermal collection to test various times and techniques of collection. Lastly, sets of images of dermal fingerprints collected from body numbers 9 and 12 are incomplete due to errors during fingerprint collection.

Pre-embalming, there were 102 epidermal fingerprints collected before initial perfusion of the body with Thiel embalming fluid and 1660 were collected after perfusion was completed (Table 4.2.2, Table 4.2.3). There were 1294 fingerprints collected using black powder and 2099 fingerprints collected using photography (Table 4.2.2, Table 4.2.3, Table 4.2.4). Among the fingerprints collected using photography, these consisted of 1049 pre-powder and 1050 post-powder images taken either before the application of black powder or after the lifting of black powder fingerprints.

4.2.2.2 Procedures

The fingerprints were assessed for quality by the author, who is not a trained fingerprint expert, using the Scottish Police Authority procedure for fingerprint and finger mark quality assessment (personal communication, J. Scott 2018), this formed a baseline for quality control and was used to determine which prints were selected for provision to the fingerprint experts for further analysis. One of three quality categories was assigned to each fingerprint:

1. unsuitable for comparison,

2. suitable for manual comparison,
3. suitable for comparison with IDENT1 software.

Examples of fingerprints with the three quality categories assigned by the author are included in Figure 4.2.3. All quality assessment categories were assigned subjectively. There are no formal requirements for assigning the category 1 and 2 quality to a fingerprint or finger mark. The fingerprint or finger mark had to contain a minimum of 8 second-level minutiae characteristics to meet the quality of category 3. Fingerprints collected using black powder were assessed using a magnifying glass. Fingerprints collected using photography were assessed in their original image form visualised on a computer screen.

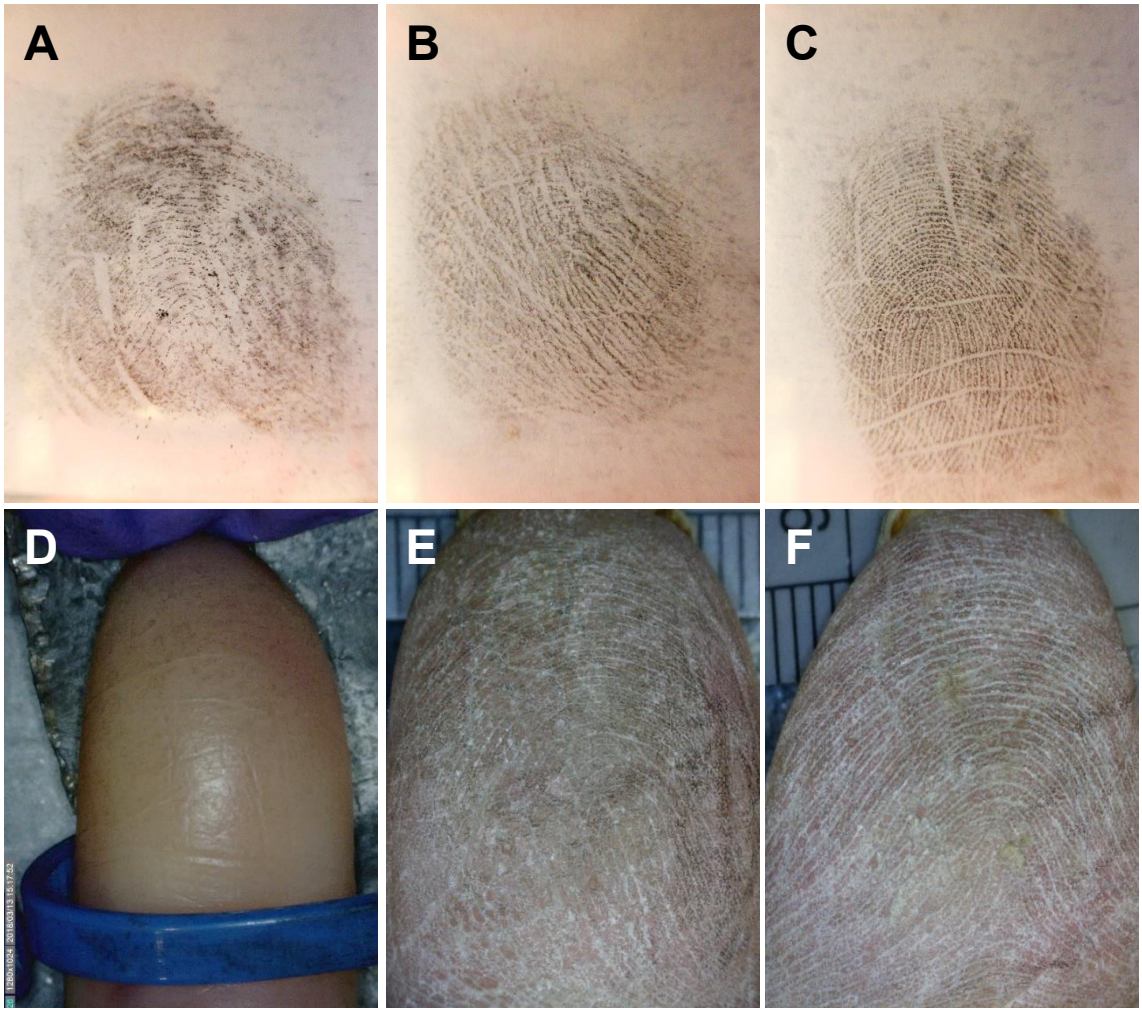

Figure 4.2.3 Examples of fingerprint quality categories. A – fingerprint collected by black powder quality category 1. B – fingerprint collected by black powder quality category 2. C – fingerprint collected by black powder quality category 3. D – fingerprint collected by photography (post-powder) quality category 1. E – fingerprint collected by photography (post-powder) quality category 2. F – fingerprint collected by photography (post-powder) quality category 3.

The usability of fingerprints was also assessed by re-grouping of quality categories assigned to all fingerprints by the author. Fingerprints assigned quality category 1 were classed as ‘unusable’. Quality categories and 2 and 3 were grouped and classed as ‘usable’.

Quality of fingerprints was also assessed quantitatively by the author via counting and comparing the minutiae numbers within an area of interest (approximately 1 cm^2) in a subsample of collected fingerprints (n = 120). The subsample consisted of 20 matched pairs of epidermal-dermal fingerprints repeated in three equal groups according to the fingerprint collection technique (Table 4.2.5). The subsample selection was based on the pool of all epidermal fingerprints collected using a black powder that had their dermal and photographic counter-prints. An online random number generator (RANDOM.ORG, 2020) was employed to select the 20 epidermal fingerprints collected using powder and the rest was complementary to the initial 20 epidermal fingerprints. Epidermal and dermal fingerprints collected using black powder were scanned (Epson Perfection 4990 Photo, resolution 1000 dpi) and analysed in digital image format. Images of all fingerprints, regardless of collection technique, were scaled using Fiji software (Schindelin *et al.*, 2012). In the case of missing scale in some of the photographs of digits, powder counter-prints were used for setting the scale of photographs.

Table 4.2.5 Number of fingerprints used for comparison of minutiae numbers.

Collection technique	**Skin layer**	
	Epidermal	Dermal
Powder	20	20
Pre-powder photography	20	20
Post-powder photography	20	20

The area of interest was selected in each image keeping the peak/centre of the core pattern in the centre of the quadrangular selection (Figure 4.2.4). The selection and subsequent adjustments were performed using Fiji software (Schindelin *et al.*, 2012). The area of interest was selected with a quadrangle that had a side with a length of 10 mm and its bottom was kept parallel with the most distal digit crease on the palmar surface (or its impression) (Figure 4.2.5). In cases where the most distal digital crease or the impression of the crease was

absent, the bottom of the photograph/address label and sides of the image were used to align the digit.

Figure 4.2.4 Area of interest (white quadrangle) selected for minutiae analysis in a dermal fingerprint collected using post-powder photography. White arrow points towards the peak in core pattern according to which the selection was centred.

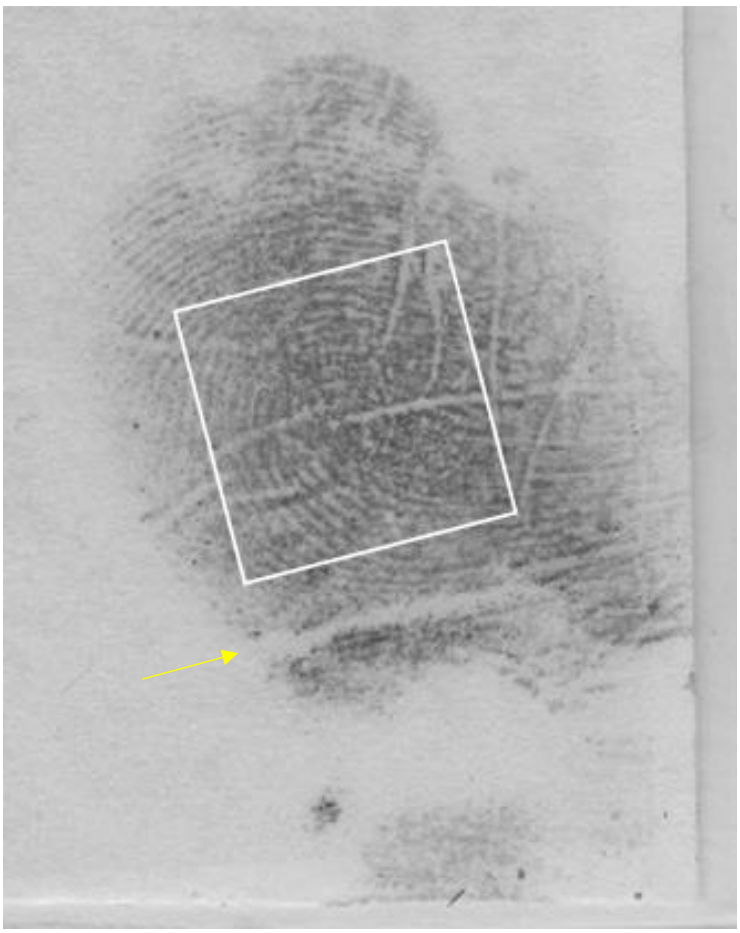

Figure 4.2.5 Selected area of interest in an epidermal fingerprint collected using black powder. Yellow arrow points towards the impression of the most distal digital crease on the palmar surface used for orientation of the quadrangular selection.

Each area of interest was cropped out of the image and saved in tagged image file format (TIFF). All subsequent images were adjusted to the size of 600 × 600 pixels. Also, images of powder fingerprints were flipped along their horizontal axis to facilitate the same orientation of features as in the photographs of digits. The image analysis was performed using laptop Lenovo V330-15IKB model 81AX with display resolution 1920 × 1080 pixels, 141 pixels per inch with antiglare. Minutiae were counted (Figure 4.2.6) and the numbers were recorded in a spreadsheet. The images were analysed without the use of any automated fingerprint identification software in the following order of groups to avoid confirmation bias: 1) all dermal fingerprints collected using pre-powder photography, 2) all dermal fingerprints collected using post-powder photography, 3) all dermal fingerprints collected using black powder, 4) all epidermal fingerprints collected using pre-powder photography, 5) all epidermal fingerprints collected using post-powder photography, 6) all epidermal fingerprints collected

using black powder. After counting the minutiae in each fingerprint, epidermal-dermal matched fingerprint pairs were compared, and matching minutiae were highlighted using a different colour (Figure 4.2.6).

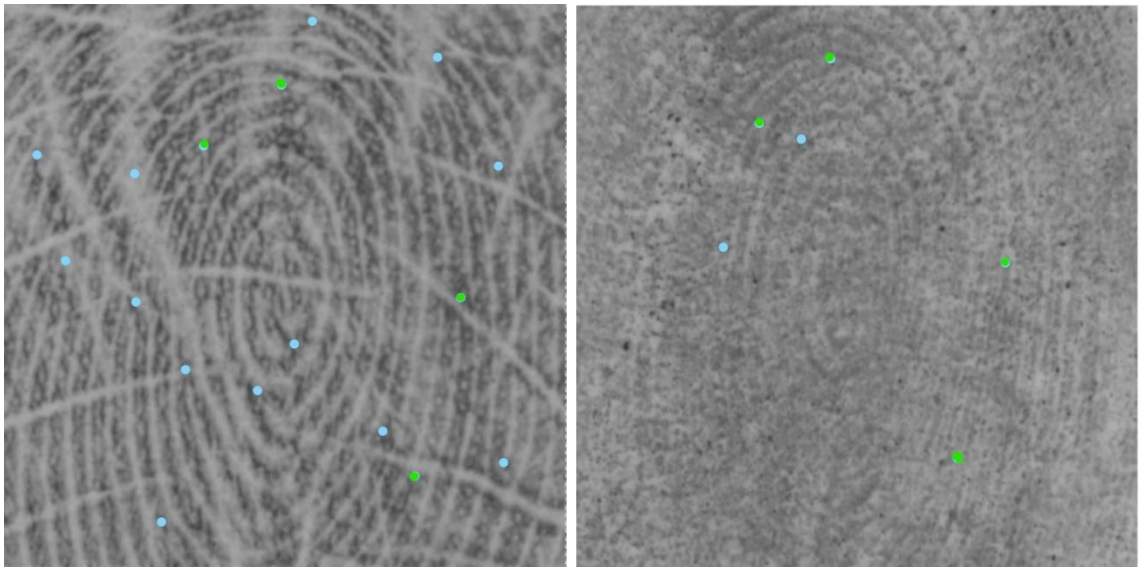

Figure 4.2.6 Area of interest selected for minutiae analysis in a pair of matched epidermal (A) and dermal (B) fingerprints collected using black powder. Blue points signify minutiae exclusive for the fingerprint, green points signify matching minutiae.

After a month, the counting of minutiae was performed again in all images. The analysis was performed in the same manner (the order of fingerprints grouped by skin layer and collection technique was maintained) by the same observer so the estimation of the intra-observer agreement for minutiae counting method could be performed.

4.2.2.3 Data analysis

4.2.2.3.1 Quality and usability

Intra-observer reliability of fingerprint quality and usability assessment was estimated using the Krippendorff alpha reliability coefficient (α). Confidence interval (95%) was calculated by bootstrapping the α coefficients (1000 iterations) according to Zapf *et al.* (2016). Alpha (α) values equal to or higher than 0.8 were considered to represent reliable data. The analyses of Krippendorff alpha coefficients and calculation of their 95% confidence intervals were performed using RStudio (RStudio Team, 2015).

The overview of fingerprint quality and usability was presented as absolute numbers and percentages of fingerprints found in each quality/usability category split by skin layer and fingerprint collection technique.

The effect of the skin layer and fingerprint collection technique was analysed using a generalised ordinal logistic regression for quality assessment data. The quality assessment data violated the proportional odds/parallel lines assumption of ordinal logistic regression, therefore generalised ordinal logistical model was applied as suggested by Williams (2016). Average adjusted predictions were calculated and used to describe the results of the applied generalised ordinal logistic regression model (Williams, 2019). Average adjusted predictions of the effect skin layer had on quality category assessment were calculated for each category of quality assessment. Average adjusted predictions of the effect fingerprint collection technique had on quality category assessment were calculated for each category of quality assessment. Average adjusted predictions of the combined effect of the skin layer and collection technique had on quality category assessment were also calculated. Generalised ordinal logistical model and average adjusted predictions for quality assessment data were estimated using software STATA 16 (StataCorp, 2019).

4.2.2.3.2 Minutiae

The concordance correlation coefficient was calculated from generalised linear negative binomial regression model of total minutiae found in each area of interest to estimate intra-observer agreement of minutiae. The intra-observer agreement was calculated separately for fingerprints collected using powder, pre, and post-powder photography. The concordance correlation coefficient calculation from the regression model was chosen due to the non-gaussian distribution of minutiae counts for each category of collection technique and according to the guidelines published by Nakagawa and Schielzeth (2010) and methods suggested by Carrasco and Jover (2003) and Josep Carrasco (personal communication, J. Carrasco 2020). RStudio was used to fit the generalised linear negative binomial model to minutiae counts and to calculate the concordance correlation coefficient for intra-observer agreement (RStudio Team, 2015).

The numbers of minutiae observed on epidermal and dermal skin layers as well as the numbers of matching minutiae and minutiae exclusive to either epidermal or dermal layer were summarised by means, medians, and ranges for each category of fingerprint collection techniques. The normality of the numbers of minutiae observed on epidermal and dermal skin layers was tested in each category of fingerprint collection technique using the Kolmogorov-Smirnov test. The difference between the numbers of observed minutiae in epidermal and dermal fingerprints was tested using the two-way paired t-test for normally distributed data and sign test (for sufficient sample size)/exact tests for binomial distribution (for small sample size). The difference between the numbers of observed minutiae in fingerprints collected using powder, pre- and post-powder photography was tested using the Friedman test. Subsequent differences between the numbers of minutiae for pairs of collection techniques were tested using a series of sign tests. The analyses of numbers of observed minutiae were performed using Statistical Package for the Social Sciences (SPSS) software (IBM Corp, 2019).

Normality of the numbers of matching minutiae observed in epidermal-dermal fingerprint pairs collected using powder, pre- and post-powder photography was tested using the Kolmogorov-Smirnov test. The difference in the number of matching minutiae between the fingerprint collection techniques was tested using the Friedman test. The differences in the number of matching minutiae between pairs of collection techniques were tested using a series of exact tests for binomial distribution due to the insufficient sample size for the sign test. The analyses of numbers of observed minutiae were performed using SPSS software (IBM Corp, 2019).

4.2.3 Expert fingerprint assessment and comparison

4.2.3.1 Sample

A subsample of 160 fingerprints was analysed by fingerprint analysis experts as part of a fingerprint comparison study. The selected fingerprints are available in digital image format on a compact disc (shared online depository) as a part of supplementary material (Appendix 3). Forty epidermal fingerprints collected using black powder were randomly selected from all epidermal fingerprints collected by

black powder to be a core of the subsample (Table 4.2.6). The selection was performed using a random number generator (RANDOM.ORG, 2020).

Table 4.2.6 Epidermal fingerprints collected using powder selected for expert analysis. L = left hand, R = right hand, Y = yes, N = no.

Fingerprint URN	Fingerprint label	Body ID	Side	Digit	Quality	Matched status
0324	1A	06	L	2	1	Y
0326	2A	06	L	4	1	Y
0327	3A	06	L	5	2	N
0434	4A	08	R	4	2	N
0529	5A	10	L	4	1	N
0581	6A	11	L	4	3	N
0586	7A	11	R	4	3	Y
0635	8A	12	R	5	2	Y
0780	9A	15	L	3	2	Y
0787	10A	15	R	5	2	N
0887	11A	17	R	2	3	Y
1095	12A	21	R	3	2	Y
1143	13A	22	L	5	1	Y
1274	14A	25	L	2	3	N
1362	15A	27	L	5	2	N
1462	16A	29	L	5	2	N
1466	17A	29	R	4	3	Y
1509	18A	30	L	2	3	N
1510	19A	30	L	3	3	N
1557	20A	31	L	4	3	Y
1605	21A	32	L	3	2	Y
1757	22A	35	L	2	3	N
1758	23A	35	L	3	3	N
1901	24A	38	R	3	3	Y
1948	25A	39	L	4	3	N
2260	26A	45	L	4	1	N
2416	27A	48	L	5	3	N
2421	28A	48	R	5	3	Y
2572	29A	51	L	5	3	Y
2777	30A	55	R	5	3	N
2873	31A	57	R	5	3	Y
2967	32A	59	L	5	3	Y
3019	33A	60	L	3	3	Y
3077	34A	61	R	4	3	N
3078	35A	61	R	5	3	N
3123	36A	62	L	3	3	Y
3176	37A	63	L	4	3	Y
3279	38A	65	R	2	3	N
3325	39A	66	L	4	3	N
3331	40A	66	R	5	3	Y

Twenty of these selected epidermal fingerprints were paired with dermal fingerprints originating from the same digit of the same individual (i.e. matched pairs) (Table 4.2.7). The other 20 selected epidermal fingerprints were paired with

randomly selected dermal fingerprints which did not originate from the same digit of the same individual (i.e. unmatched pairs) (Table 4.2.7).

Table 4.2.7 Dermal fingerprints collected using powder selected for expert analysis. L = left hand, R = right hand, Y = yes, N = no.

Fingerprint URN	Fingerprint label	Body ID	Side	Digit	Quality	Matched status
0334	1B	06	L	2	1	Y
0336	2B	06	L	4	1	Y
0111	3B	02	R	3	2	N
0444	4B	08	R	4	2	N
0595	5B	11	R	3	2	N
0892	6B	17	L	3	2	N
0596	7B	11	R	4	2	Y
0645	8B	12	R	5	2	Y
0790	9B	15	L	3	2	Y
1048	10B	20	L	3	1	N
0896	11B	17	R	2	2	Y
1105	12B	21	R	3	1	Y
1152	13B	22	L	5	1	Y
1100	14B	21	L	3	1	N
1241	15B	24	L	3	2	N
1775	16B	35	R	5	2	N
1475	17B	29	R	4	2	Y
2011	18B	40	L	5	2	N
2113	19B	42	L	3	3	N
1566	20B	31	L	4	2	Y
1614	21B	32	L	3	2	Y
1470	22B	29	L	4	2	N
2691	23B	53	R	5	2	N
1910	24B	38	R	3	3	Y
2378	25B	47	R	3	3	N
1721	26B	34	R	3	3	N
1247	27B	24	R	4	2	N
2431	28B	48	R	5	3	Y
2582	29B	51	L	5	2	Y
2734	30B	54	R	4	3	N
2878	31B	57	R	5	1	Y
2977	32B	59	L	5	1	Y
3029	33B	60	L	3	2	Y
1666	34B	33	L	5	2	N
3244	35B	64	R	5	2	N
3133	36B	62	L	3	1	Y
3186	37B	63	L	4	3	Y
2735	38B	54	R	5	1	N
2924	39B	58	L	4	1	N
3341	40B	66	R	5	1	Y

To enable a comparison of fingerprint collection methods, photographic equivalents of selected powder epidermal and dermal fingerprints were also selected (Table 4.2.8, Table 4.2.9).

Table 4.2.8 Epidermal fingerprints collected using post-powder photography selected for expert analysis. L = left hand, R = right hand, Y = yes, N = no.

Fingerprint URN	Fingerprint label	Body ID	Side	Digit	Quality	Matched status
0303	1a	06	L	2	3	Y
0305	2a	06	L	4	2	Y
0306	3a	06	L	5	2	N
0409	4a	08	R	4	2	N
0504	5a	10	L	4	1	N
0556	6a	11	L	4	2	N
0560	7a	11	R	4	3	Y
0613	8a	12	R	5	1	Y
0755	9a	15	L	3	2	Y
0761	10a	15	R	5	1	N
0858	11a	17	R	2	3	Y
1069	12a	21	R	3	2	Y
1119	13a	22	L	5	1	Y
1257	14a	25	L	2	3	N
1337	15a	27	L	5	1	N
1438	16a	29	L	5	2	N
1441	17a	29	R	4	2	Y
1485	18a	30	L	2	3	N
1486	19a	30	L	3	2	N
1537	20a	31	L	4	3	Y
1581	21a	32	L	3	2	Y
1732	22a	35	L	2	2	N
1733	23a	35	L	3	3	N
1876	24a	38	R	3	3	Y
1923	25a	39	L	4	2	N
2235	26a	45	L	4	1	N
2392	27a	48	L	5	3	N
2396	28a	48	R	5	2	Y
2547	29a	51	L	5	3	Y
2751	30a	55	R	5	3	N
2855	31a	57	R	5	3	Y
2942	32a	59	L	5	2	Y
2992	33a	60	L	3	2	Y
3051	34a	61	R	4	2	N
3052	35a	61	R	5	2	N
3098	36a	62	L	3	3	Y
3151	37a	63	L	4	2	Y
3257	38a	65	R	2	3	N
3300	39a	66	L	4	2	N
3305	40a	66	R	5	2	Y

Table 4.2.9 Dermal fingerprints collected using post-powder photography selected for expert analysis. L = left hand, R = right hand, Y = yes, N = no.

Fingerprint URN	Fingerprint label	Body ID	Side	Digit	Quality	Matched status
0319	1b	06	L	2	2	Y
0321	2b	06	L	4	2	Y
0083	3b	02	L	5	3	N
0421	4b	08	R	4	2	N
0571	5b	11	L	4	2	N
0879	6b	17	L	4	2	N
0572	7b	11	R	4	2	Y
0621	8b	12	R	5	2	Y
0775	9b	15	L	3	2	Y
1033	10b	20	R	5	2	N
0874	11b	17	R	2	1	Y
1081	12b	21	R	3	1	Y
1139	13b	22	L	5	1	Y
1085	14b	21	L	2	2	N
1226	15b	24	L	5	2	N
1751	16b	35	L	5	1	N
1453	17b	29	R	4	2	Y
1996	18b	40	L	2	2	N
2098	19b	42	L	3	2	N
1553	20b	31	L	4	2	Y
1601	21b	32	L	3	2	Y
1457	22b	29	L	2	2	N
2667	23b	53	L	3	2	N
1888	24b	38	R	3	2	Y
2354	25b	47	L	4	2	N
1697	26b	34	L	4	2	N
1223	27b	24	L	5	2	N
2407	28b	48	R	5	3	Y
2567	29b	51	L	5	2	Y
2715	30b	54	R	5	2	N
2863	31b	57	R	5	1	Y
2962	32b	59	L	5	1	Y
3014	33b	60	L	3	1	Y
1653	34b	33	R	4	3	N
3220	35b	64	R	5	2	N
3118	36b	62	L	3	2	Y
3171	37b	63	L	4	2	Y
2716	38b	54	R	2	1	N
2909	39b	58	L	4	1	N
3317	40b	66	R	5	1	Y

4.2.3.2 Observers

Quality assessment and comparison of the epidermal and dermal fingerprints subsample was performed by trained fingerprint analysis experts from Scottish Police Authority in the United Kingdom - Scotland (n = 7), Centrale Directie van Technishe & Wetenschappelijke Politie in Brussels, Belgium (n = 4), Nationellt Forensiskt Centrum in Stockholm, Sweden (n = 4), and Crime Print Section of National Criminal Investigation Group in New Zealand (n = 1). The information

about years of experience for each of the experts taking part in the study is included in Table 4.2.10. The table also contains the experts who did not complete the analysis of the full dataset; their data is presented in the results section but is excluded from all statistical analyses. University of Dundee ethics committee approval for working with human participants was sought and granted (Appendix 4). The experts were recruited via email (Appendix 5) with an attached participant information sheet (Appendix 6). Upon participation, they were asked to sign a consent form (Appendix 7) and were assigned a random participant number which was substituted with a letter for data analysis and presentation purposes.

Table 4.2.10 Fingerprint examiners taking part in the fingerprint comparison study. NA – answer not provided. UK – United Kingdom, BE – Belgium, SWE – Sweden, NZ = New Zealand. Y = yes, N = no.

Expert	Country	Years of experience	Fingerprints analysed	Included in the majority of statistical analyses
A	UK	16	Full dataset	Y
B	UK	14	Full dataset	Y
C	UK	22	Full dataset	Y
D	UK	29	Full dataset	Y
E	UK	5	½ Powder fingerprints dataset	N
F	UK	1	½ Powder fingerprints dataset Full Photo fingerprints dataset	N
Q	UK	NA	Full dataset	Y
H	BE	2	Full dataset	Y
I	BE	4	Full dataset	Y
N	BE	NA	Full dataset	Y
O	BE	2	Full dataset	Y
J	SWE	2	Full dataset	Y
K	SWE	< 1	Full Powder fingerprints dataset	N
L	SWE	NA	11 Powder fingerprints	N
M	SWE		½ Powder fingerprints dataset	N
P	NZ	29	Full dataset	Y

Since the experts are from different agencies employing various approaches and standards of fingerprint examination, fingerprint assessment and comparison procedures vary in certain points for each country and therefore the procedures will be described in separate subsections for each group of experts according to the country they work in.

4.2.3.3 Assessment and comparison procedure – Scotland (UK)

Each Scottish fingerprint analysis expert was presented with 40 pairs of epidermal-dermal fingerprints recovered using black powder where 20 of epidermal-dermal pairs were matched (from the same digit) and 20 epidermal-dermal pairs were unmatched (not from the same digit). The epidermal set of fingerprints represented ‘ante-mortem data’ for the purposes of this task despite them being collected from deceased individuals. An example of one epidermal-dermal fingerprint pair collected using powder which was given to the experts for analysis is included in Appendix 8. For each given fingerprint, the experts were asked to record its quality

1. unsuitable for comparison,
2. suitable for manual comparison,
3. suitable for comparison using IDENT1 software.

The experts were then asked to analyse each pair of fingerprints and record the result of the analysis as

- identification (two analysed fingerprints are from the same individual),
- exclusion (two analysed fingerprints are not from the same individual),
- insufficient (one or both fingerprints are of insufficient quality to establish an identification or an exclusion),
- unable to exclude (the expert is unable to establish identification but does not rule out a possible exclusion).

The experts were also asked to record the number of minutiae marked up on each fingerprint and the number of matching minutiae for each pair of given fingerprints. The numbers of minutiae were recorded in four categories: 0, low (< 10), medium (10 – 20), high (> 20). The example of the recording form is included in Appendix 9. Fingerprint comparators were used by the Scottish experts, apart from the expert Q who did not have access to fingerprint comparators and used a magnifying glass instead.

After the analysis of fingerprints collected using black powder was completed, the same experts were presented with a set of 40 pairs of epidermal-dermal photographs of digits (fingerprints collected using photography) which were photographic equivalents of the 40 pairs collected using black powder selected for the comparison by the experts. Twenty epidermal-dermal pairs were from the same digit and 20 epidermal-dermal pairs were not from the same digit. After the consultation with the Scottish fingerprint examiners, they recommended printed images for analysis and comparison purposes. The photographs were printed in black and white (8-bit) on a photographic paper in sets of 10 images per one sheet of photographic paper. The adjustments of images to black and white setting and the printing was performed by Dundee Scottish Police Authority imaging unit according to their standards. The Scottish experts were asked to analyse the printed images in the same way as they would analyse the fingerprints collected by black powder and to record the same types of information as for the analysed fingerprints collected using black powder. An example of an epidermal-dermal fingerprint pair collected using photography which was given to the experts for analysis is included in Appendix 8. Similarly to the powder fingerprints used for the task, the epidermal set of fingerprints represented 'ante-mortem data' for the purposes of this task despite the fact that the photographs of digits were taken from deceased individuals. The author is aware that in usual situations of operational practice, the ante-mortem fingerprint sets would be available for comparison in inked/powder/digitalised format instead of a photograph of a friction ridge skin which were provided to the expert in current task. The author decided to provide the epidermal fingerprint set in photographic format to be able to compare powder and photography fingerprint collection methods in their performance on account of losing applicability to usual operational practice.

4.2.3.4 Assessment and comparison procedure – Belgium

The same sets of fingerprints provided to the previous group of experts were analysed by Belgian experts. The set of 40 pairs of fingerprints collected using black powder was scanned (Epson Expression 10000XL flatbed scanner) by an expert into an electronic TIFF format with a resolution of 500 dpi to the standards of the Belgian Biometric Identification Service. Together with 40 pairs of images representing fingerprints collected using photography (which were changed to

black and white 8-bit images with a resolution of 500 dpi), all 160 fingerprints were uploaded and aligned using AFIS software employed by Belgian Police. For each given fingerprint, the experts were asked to record its quality

1. unsuitable for comparison (the number of found minutiae points was less than eight),
2. suitable for manual comparison (the number of found minutiae points was between eight and eleven),
3. suitable for comparison using AFIS software employed by Belgian Police (the number of found minutiae points was twelve and above).

The experts were asked to analyse and compare each pair of fingerprints in a software CSIpix Comparator 4 (Intelligent System Solutions Corporation, Canada). The results of the analysis were recorded in a way that reflected different practices of fingerprint comparison reporting in Belgium when compared to the practices employed in Scotland.

- An identification was reported in cases with a minimum of 12 minutiae points matching in both fingerprints to establish the two fingerprints are from the same individual.
- An exclusion was reported in cases where two analysed fingerprints had enough information proving they did not originate from the same individual.
- Identification outcome was reported insufficient in cases where there were less than 8 matching minutiae points in both fingerprints, but an identification or an exclusion could not be confirmed.
- Identification outcome was reported as unable to exclude in cases where the expert was unable to establish an identification but did not rule out a possible exclusion due to the low quality of at least one of the two compared fingerprints.

The experts were also asked to record the number of minutiae marked up on each fingerprint and the number of matching minutiae for each pair of given fingerprints. The numbers of minutiae were recorded in four categories: 0, low (< 8), medium (8 – 11), high (≥ 12).

4.2.3.5 Assessment and comparison procedure – Sweden

The same sets of fingerprints provided to the previous group of experts were analysed by Swedish experts. The set of 40 pairs of fingerprints collected using black powder was re-scanned (Epson Perfection 4990 Photo) by a Swedish

expert into an electronic TIFF format with a resolution of 1000 dpi to meet the requirements of Swedish forensic fingerprint examiners. Together with 80 original red – green – blue (RGB) (32-bit) images representing fingerprints collected using photography, all 160 fingerprints were uploaded, analysed, and compared (side-by-side) in Adobe Photoshop software. For each given fingerprint, the experts were asked to record its quality. There were only two categories given, to reflect their normal work practices:

- 1 – unsuitable for comparison and
- 2 + 3 – suitable for comparison,

categories 2 and 3 were grouped into one due to the same minimum fingerprint quality requirements for software and manual comparison the experts have in this country. The experts were asked to analyse each pair of fingerprints and record the result of the analysis as

- identification (two analysed fingerprints are from the same individual),
- exclusion (two analysed fingerprints are not from the same individual),
- insufficient/inconclusive (no matching performed due to insufficient quality of the fingerprints), and
- unable to exclude (the expert is unable to establish identification but does not rule out a possible exclusion and needs more information for conclusive identification result).

The experts were also asked to record the number of minutiae marked up on each fingerprint and the number of matching minutiae for each pair of given fingerprints. The numbers of minutiae were recorded in the same four categories as for the experts in Scotland: 0, low (< 10), medium (10 – 20), high (> 20).

4.2.3.6 Assessment and comparison procedure – New Zealand

The expert from New Zealand performed a comparison of the fingerprint dataset analysed by Swedish experts using digital versions of the same fingerprints collected using black powder original RGB (32-bit) images of fingerprints collected using post-powder photography. All 160 fingerprints were uploaded, analysed, and compared (side-by-side) in Adobe Photoshop software. For each given fingerprint, the expert was asked to record its quality

1. unsuitable for comparison,
2. suitable for manual comparison,

3. suitable for comparison using AFIS software employed by New Zealand Police (the minimum number of found minutiae points accepted is six minutiae).

The results of the fingerprint comparison were recorded in the same manner as for the experts in Scotland:

- identification (two analysed fingerprints are from the same individual),
- exclusion (two analysed fingerprints are not from the same individual),
- insufficient (one or both fingerprints are of insufficient quality to establish an identification or an exclusion), and
- unable to exclude (the expert is unable to establish an identification but does not rule out a possible exclusion).

The numbers of minutiae were recorded in the same four categories as for the experts in Scotland: 0, low (< 10), medium (10 – 20), high (> 20).

4.2.3.7 Data analysis

4.2.3.7.1 Quality and usability

The quality assessment of fingerprints performed by all fingerprint examiners was summarised by the number and percentage of fingerprints assigned by each expert into three quality categories, grouped by the skin layer and fingerprint collection techniques. The usability assessment of fingerprints performed by all fingerprint examiners was summarised by the number of fingerprints assigned by each expert as usable/unusable and grouped by the skin layer and fingerprint collection technique.

Inter-observer reliability of fingerprint quality and usability assessment was estimated using the Krippendorff alpha reliability coefficient (α). Confidence intervals (95%) were calculated by bootstrapping the α coefficients (1000 iterations) according to Zapf *et al.* (2016). α values equal to or higher than 0.8 were considered to represent reliable data. Inter-observer reliability of fingerprint quality and usability assessment was calculated for fingerprints grouped by the skin layer and by fingerprint collection technique (powder and post-powder photography). Inter-observer reliability of fingerprint quality and usability assessment was always calculated twice – including and excluding the expert Q. This dual calculation was performed due to the expert Q having no access to a fingerprint comparator in contrast to the other UK experts and performing the

analysis using magnifying glass only (see section 4.2.3.3) and thus being the only examiner who did not follow exactly the same methodology as the others. Inter-observer reliability of fingerprint quality assessment was estimated separately for experts from Belgium, experts from the UK who completed the analysis for the full dataset (n = 5), and the UK experts without the expert Q (n = 4). Inter-observer reliability of fingerprint quality assessment was also estimated between the author baseline assessment and each of the UK experts who completed the analysis of the full dataset. Inter-observer reliability of fingerprint usability assessment was estimated separately for Belgian experts, UK experts who completed the analysis of the full dataset, UK experts without the expert Q, experts from all countries who completed the analysis for the full dataset (n = 11), and the same experts from all countries without the expert Q (n = 10). The calculations of Krippendorff alpha coefficients and calculation of their 95% confidence intervals were performed using RStudio function kripp.alpha from the package 'irr' and package 'kripp.boot' (RStudio Team, 2015; Proutskova and Gruszczynski, 2017; Gamer, 2019). The R script together with data source files can be found in a shared data folder for thesis supplementary materials (Appendix 10).

4.2.3.7.2 Minutiae

The minutiae observed on fingerprints were summarised by the number and percentage of fingerprints assigned into one of four minutiae number ranges grouped by the skin layer and fingerprint collection techniques. The minutiae number ranges differ between Belgium, a country employing a numeric approach in fingerprint examination, and the rest of the countries that use a holistic approach in fingerprint examination. The data collected from all experts was presented.

Inter-observer reliability of minutiae assessment was estimated using the Krippendorff alpha reliability coefficient (α). Confidence intervals (95%) were calculated by bootstrapping the α coefficients (1000 iterations) according to Zapf *et al.* (2016). α values equal to or higher than 0.8 were considered to represent reliable data. Inter-observer reliability of minutiae assessment was calculated for fingerprints grouped by the skin layer and by fingerprint collection technique (powder and post-powder photography). Inter-observer reliability of minutiae assessment was estimated separately for experts from Belgium, experts from the

UK who analysed the full dataset (n = 5), the same UK experts without the expert Q (n = 4), experts from the UK combined with the Swedish expert and the expert from New Zealand – all of whom analysed the full dataset (n = 7), and the same group of experts without the expert Q (n = 6). The calculations of Krippendorff alpha coefficients and calculation of their 95% confidence intervals were performed using RStudio function kripp.alpha from the package 'irr' and package 'kripp.boot' (RStudio Team, 2015; Proutskova and Gruszczynski, 2017; Gamer, 2019). The R script together with data source files can be found in a shared data folder for thesis supplementary materials (Appendix 10).

For the experts from Belgium, the minutiae number ranges were also compared to the quality assessment of fingerprints, since the quality categories reported by the experts from this country were based on the same minutiae number ranges the experts utilised. Consistency scores of minutiae and quality assessment were expressed as the number of fingerprints that had the same minutiae number range as the quality category within each skin layer and collection technique category. The minutiae number ranges '0' and '1' were grouped into one to facilitate the comparison between minutiae number ranges and quality categories.

4.2.3.7.3 Epidermal-dermal fingerprint comparison

The results of epidermal-dermal fingerprint comparison were summarised by the number of the experts assigning each fingerprint pair one of five comparison outcome categories, grouped by fingerprint collection techniques. The comparison outcomes were also grouped by matching/not matching the expected comparison outcome of matched (originating from the same digit) and unmatched (originating from different digits) epidermal-dermal fingerprint pairs. The data collected from all experts was presented.

The percentages of epidermal-dermal fingerprint pairs that could not be identified or excluded (i.e. those classified as 'insufficient', 'unable to exclude', and 'NA') were calculated for fingerprint examiners who completed the analysis of the full dataset within a collection technique category. False negative exclusions were not included in these calculations.

The performance of the experts in epidermal-dermal fingerprint comparison was also summarised by calculating the accuracy per class for each expert who completed the analysis of the full dataset within at least one of the two fingerprint collection technique categories. The total number of correct identifications, correct exclusions and inconclusive outcomes in fingerprint pairs, in which all experts agreed upon the inconclusive result, was summed up and divided by the total number of epidermal-dermal fingerprint pairs present in each collection technique category (40 fingerprint pairs). The number was then multiplied by 100 to calculate percentage of examiners' accuracy. Inconclusive fingerprint comparison outcomes in which all the experts agreed upon such outcome were included among the correct comparison outcome according to the latest recommendations published by Dror and Scurich (2020), where the authors stress the importance of inclusion of such data in any error rate fingerprint studies.

The fingerprint comparison outcomes were also compared to the expert assessment of fingerprint usability. The number of fingerprint pairs where at least one fingerprint was deemed unusable and the experts were able to arrive at an identification or exclusion outcome was calculated. Only the data collected from experts who completed the analysis of the full dataset was presented.

Inter-observer reliability of fingerprint comparison outcomes (with five and three outcome categories) was estimated using the Krippendorff alpha reliability coefficient (α). Confidence intervals (95%) were calculated by bootstrapping the α coefficients (1000 iterations) according to Zapf *et al.* (2016). α values equal to or higher than 0.8 were considered to represent reliable data. Inter-observer reliability of fingerprint comparison outcome assessment (into five and three categories respectively) was calculated for fingerprints grouped by fingerprint collection technique (powder and post-powder photography). Inter-observer reliability of fingerprint comparison outcome assessment (into five and three categories) was estimated separately for experts from Belgium, experts from the UK who completed the whole dataset, the same UK experts without the expert Q, all experts form all countries who completed the analysis of the full dataset, and the same experts without the expert Q. The calculations of Krippendorff alpha coefficients and calculation of their 95% confidence intervals were performed

using RStudio function kripp.alpha from the package ‘irr’ and package ‘kripp.boot’ (RStudio Team, 2015; Proutskova and Gruszczynski, 2017; Gamer, 2019). The R script together with data source files can be found in a shared data folder for thesis supplementary materials (Appendix 10).

4.3 Results

4.3.1 Baseline fingerprint assessment

4.3.1.1 Quality and usability

Krippendorff alpha coefficient (α) for estimating intra-observer reliability of fingerprint quality and usability assessment are included in Table 4.3.1. Both α values are below 0.8, which is a coefficient cited for reliable data (Krippendorff, 2013). However, confidence intervals for both α coefficients include 0.8 value.

Table 4.3.1 Krippendorff alpha coefficients (α) for intra-observer variability in fingerprint quality and usability assessment. CI = confidence interval.

Variable	α	95% CI min	95% CI max
Quality	0.793	0.742	0.843
Usability	0.698	0.520	0.856

Figure 4.3.1 shows the number of epidermal and dermal fingerprints in each of the three quality categories split by the collection technique as assessed by the author. As was mentioned in section 4.2.1.2, discrepancies between the number of collected fingerprints for each skin layer and collection technique exist. The variation in the numbers is due to difficulties photographing certain digits and collection errors.

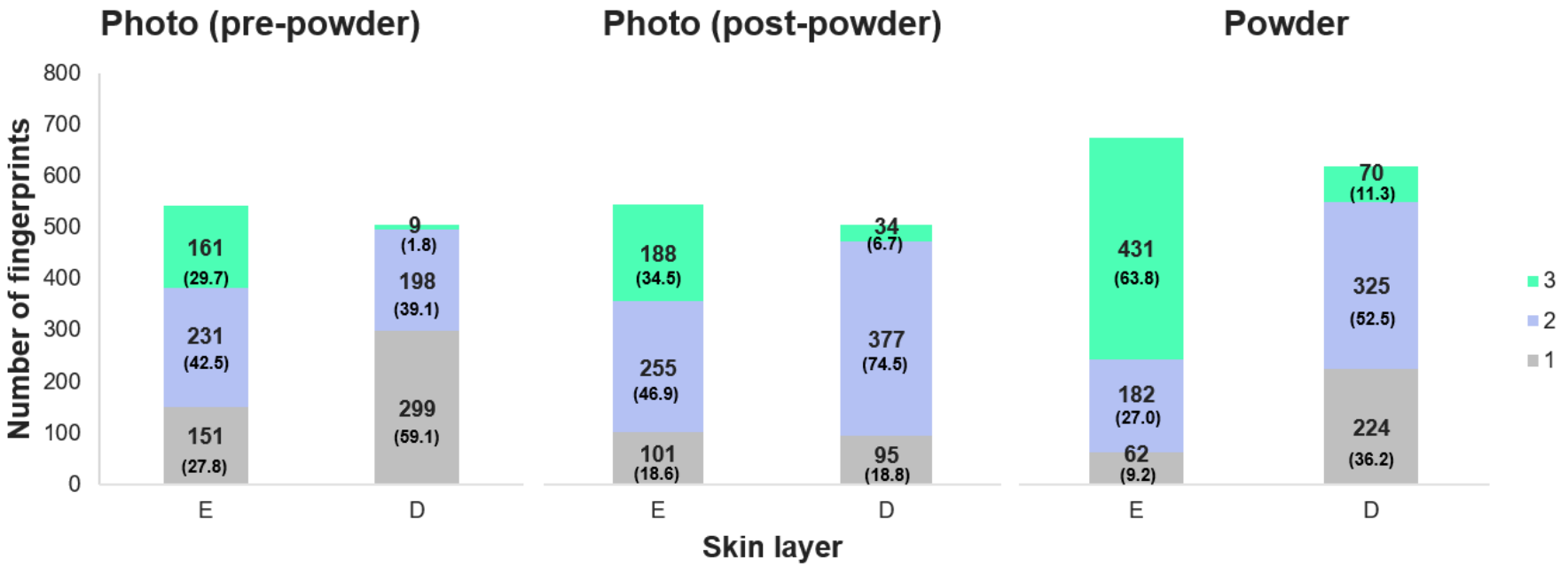

Figure 4.3.1 Baseline fingerprint quality assessment. Numbers in brackets indicate percentages of fingerprint numbers within each of the bars. E = epidermal, D = dermal. 1 – unsuitable for comparison, 2 – suitable for manual comparison, 3 – suitable for comparison using IDENT1 software.

As is shown in Figure 4.3.1, there was a higher proportion of epidermal fingerprints labelled as Category 3 (fingerprints suitable for IDENT1 upload) to dermal fingerprints for all three collection techniques. The powder had the highest proportion of category 3 epidermal fingerprints (63.8%) when compared to other collection techniques. Photography had half of the proportions of category 3 epidermal fingerprints (29.7% and 34.5%) when compared to powder (63.8%). However, there were similar proportions of category 3 epidermal fingerprints when comparing the two photography collection techniques. There was a slightly higher proportion of category 3 epidermal fingerprints collected using photography post-powder (34.5%) than pre-powder (29.7%). The dermal skin layer showed similar trends in proportions of category 3 fingerprints when comparing collection techniques. Powder collection technique had the highest proportion of category 3 dermal fingerprints (11.3%) when compared to other collection techniques. Post-powder photography had a higher proportion of category 3 dermal fingerprints (6.7%) when compared to pre-powder photography (1.8%).

When comparing category 2 (fingerprints suitable for manual comparison) between epidermal and dermal fingerprints, there was a slightly higher number of epidermal fingerprints for the pre-powder photography collection technique (42.5% epidermal, 39.1% dermal). The proportions of dermal fingerprints in category 2 were higher than the proportion of epidermal fingerprints for post-powder photography (46.9% epidermal, 74.5% dermal) and almost double the proportion of fingerprints for powder (27% epidermal, 52.5% dermal). When comparing fingerprint collection techniques in quality 2 category, the highest number and proportion of both epidermal and dermal fingerprints were in the post-powder photography collection technique.

For the category 1 (fingerprints unsuitable for comparison), there were lower proportions of epidermal fingerprints compared to the proportions in dermal fingerprints numbers for powder (9.2% epidermal, 36.2% dermal) and pre-powder photography (27.8% epidermal, 59.1% dermal) collection techniques. Epidermal and dermal fingerprints had almost equal fingerprint percentages classed as category 1 in the post-powder photography group (18.6% epidermal, 18.8% dermal). When comparing fingerprint collection techniques in quality 1 category,

the fingerprint collection technique which had the greatest number of both epidermal and dermal fingerprints that were assigned as category 1 was pre-powder photography.

Based on the presented quality results, only a subsample of fingerprints collected using black powder and post-powder photography was selected for analysis and comparison by fingerprint examiners (section 4.3.2).

To further examine which of the collected prints would be considered ‘suitable for comparison’ by a fingerprint expert and which would be rejected as ‘unsuitable for comparison’, categories 2 and 3 were combined, since prints falling into either of these categories would be suitable for comparison and therefore ‘useable’. These numbers were compared to the prints assigned category 1, where the print would be rejected as unsuitable for comparison and therefore unusable (Figure 4.3.2). When comparing skin layers within each collection technique, prints recovered from the epidermal layer had more usable fingerprints than those recovered from the dermal layer for both the powder collection technique (90.8% epidermal, 63.8% dermal) and pre-powder photography (73.2% epidermal, 40.9% dermal). The number of usable/unusable epidermal and dermal fingerprints collected using post-powder photography was close to equal (Figure 4.3.2).

When comparing the fingerprint numbers and percentages based on collection techniques, powder gives the greatest number of usable epidermal fingerprints (90.8%), and post-powders photography gives the greatest numbers of usable dermal fingerprints (81.2%) (Figure 4.3.2).

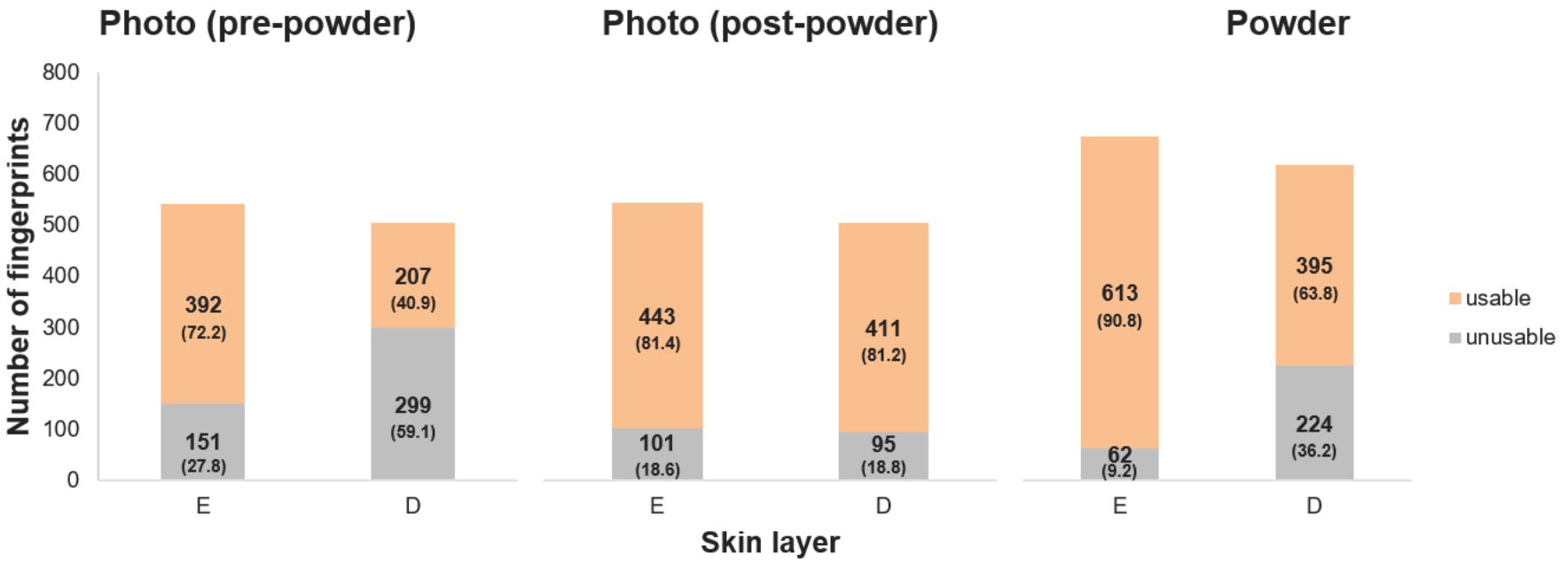

Figure 4.3.2 Baseline fingerprint usability assessment. Numbers in brackets indicate percentages of fingerprint numbers within each of the bars. E = epidermal, D = dermal.

To describe the effects of the skin layer and collection technique on quality assessment of all collected fingerprints, generalised ordinal logistical regression was performed. Pre- and post-powder photography collection techniques were pooled for this analysis. The results of the generalised ordinal logistical model for quality assessment data are reported as average adjusted predictions presented in corresponding tables and figures below. Table 4.3.2 and Figure 4.3.3 show that if all other variables are kept constant, dermal fingerprints are more than twice as likely as epidermal fingerprints to be assigned category 1 quality (37.9% dermal, 17.8% epidermal), about 1.4 times more likely to be assigned category 2 quality (55% dermal, 38.4% epidermal), and about six times less likely to be assigned category 3 quality (7.1% dermal, 43.7% epidermal). If all other variables are kept constant, 82.1% of epidermal and 62% of dermal fingerprints are classified as usable fingerprints.

Table 4.3.2 Average adjusted predictions of skin layers for each quality category. E = epidermal, D = dermal.

Quality category	Skin layer	Margin	Standard error	z	95% Confidence interval min.	95% Confidence interval max.
1	E	0.178	0.009	19.62	0.160	0.196
1	D	0.379	0.012	31.72	0.355	0.402
2	E	0.385	0.011	34.04	0.363	0.407
2	D	0.550	0.012	44.56	0.526	0.574
3	E	0.437	0.011	38.49	0.415	0.459
3	D	0.071	0.006	11.18	0.059	0.084

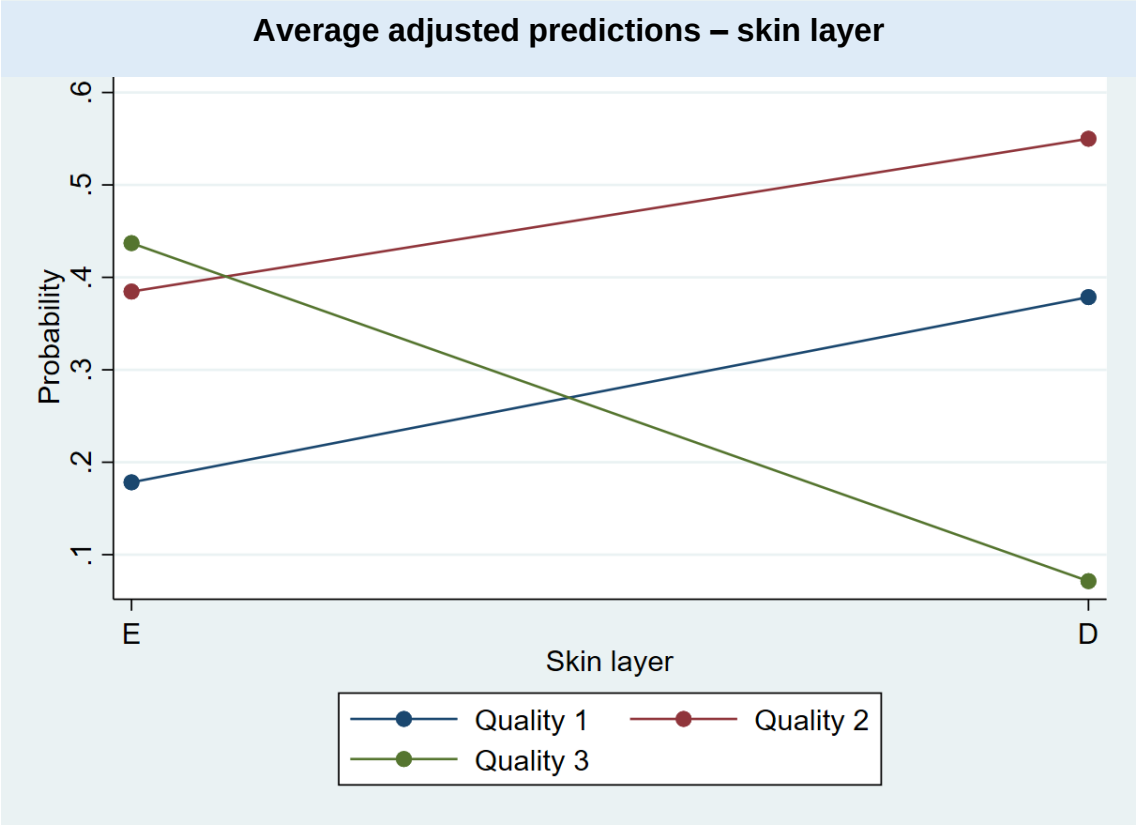

Figure 4.3.3 Average adjusted predictions of the skin layer for each quality category. E = epidermal, D = dermal. Quality 1 – unsuitable for comparison, Quality 2 – suitable for manual comparison, Quality 3 – suitable for comparison using IDENT1 software (minimum of 8 minutiae detected).

Table 4.3.3, and Figure 4.3.4 show that if all other variables are kept constant, fingerprints collected using photography (both pre- and post-powder pooled) are 1.4 times more likely than fingerprints collected using black powder to be assigned category 1 quality (30.7% photography, 22.1% powder), 1.2 times more likely to be assigned category 2 quality (50% photography, 40.5% powder), and almost two times less likely to be assigned category 3 quality (19.2% photography, 37.3% powder). If all other variables are kept constant, 77.8% of fingerprints collected using black powder and 69.2% of fingerprints collected using photography are classified as usable fingerprints.

Table 4.3.3 Average adjusted predictions of fingerprint collection techniques for each quality category. Pre- and post-powder photographs pooled. 1 – unsuitable for comparison, 2 – suitable for manual comparison, 3 – suitable for comparison using IDENT1 software (minimum of 8 minutiae detected).

Quality category	Collection technique	Margin	Standard error	z	95% Confidence interval min.	95% Confidence interval max.
1	Powder	0.221	0.011	19.61	0.199	0.244
1	Photo	0.307	0.013	31.42	0.288	0.327
2	Powder	0.405	0.011	32.11	0.381	0.430
2	Photo	0.500	0.113	45.88	0.479	0.522
3	Powder	0.373	0.011	33.11	0.351	0.395
3	Photo	0.192	0.008	23.94	0.177	0.208

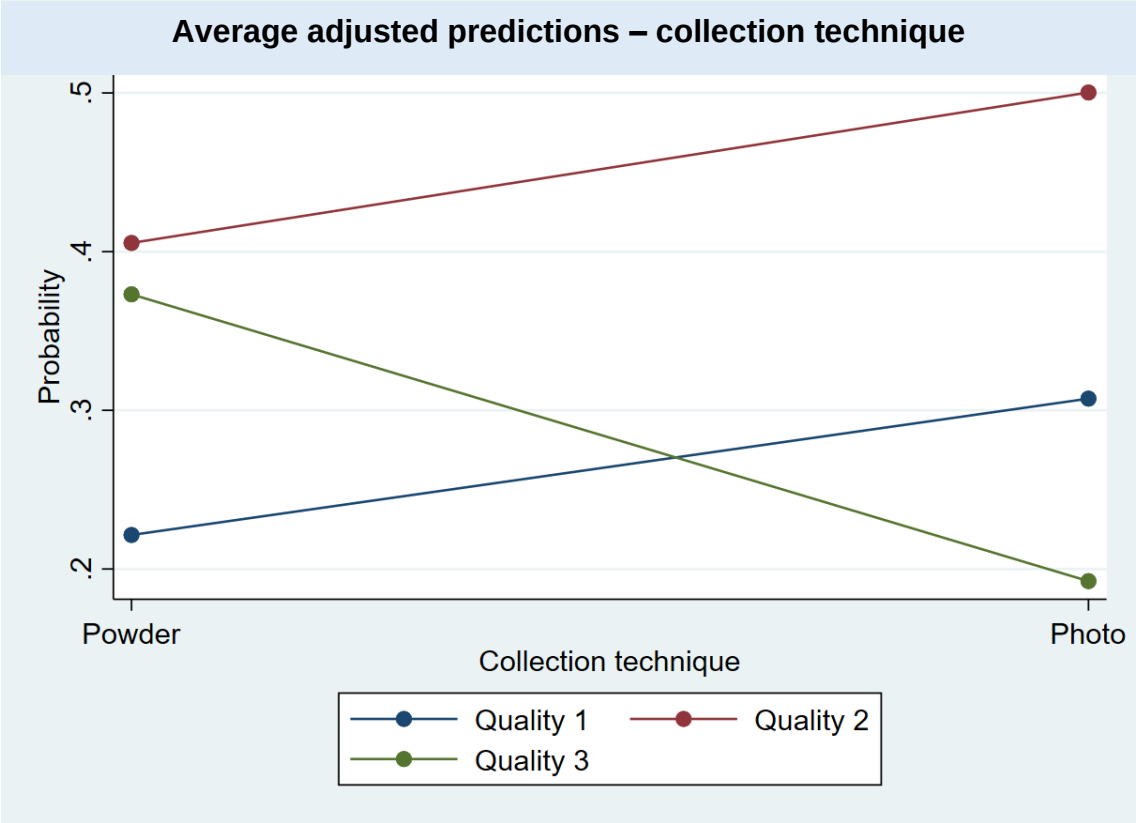

Figure 4.3.4 Average adjusted predictions of collection techniques for each fingerprint category. Pre- and post-powder photographs pooled. Quality 1 – unsuitable for comparison, Quality 2 – suitable for manual comparison, Quality 3 – suitable for comparison using IDENT1 software (minimum of 8 minutiae detected).

Table 4.3.4 and Figure 4.3.5 present the average adjusted predictions of collection technique on assigning quality to fingerprints by skin layer. There is a higher probability of obtaining category 3 fingerprints from both epidermal (1.8 times more likely) and dermal (2.8 times more likely) skin layers when collected

using powder collection technique compared to photography. There is a 1.8 times higher probability of obtaining 2 category fingerprints from the epidermal skin layer when using photography rather than powder collection technique. For the dermal skin layer, there is a slightly higher (1.1 times) probability of obtaining fingerprints that are category 2 when using powder collection technique rather than photography.

Table 4.3.4 Average adjusted predictions of collection techniques for each quality category combined with the skin layer. E = epidermal, D = dermal. 1 – unsuitable for comparison, 2 – suitable for manual comparison, 3 – suitable for comparison using IDENT1 software (minimum of 8 minutiae detected).

Quality category	**Collection technique**	**Skin layer**	**Margin**	**Standard error**	**z**	**95% Confidence interval min.**	**95% Confidence interval max.**
1	Powder	E	0.138	0.010	13.64	0.118	0.158
1	Powder	D	0.312	0.016	19.37	0.280	0.343
1	Photo	E	0.203	0.011	18.51	0.182	0.225
1	Photo	D	0.420	0.014	29.15	0.392	0.448
2	Powder	E	0.254	0.015	16.55	0.224	0.285
2	Powder	D	0.569	0.017	33.29	0.535	0.602
2	Photo	E	0.465	0.014	32.07	0.437	0.493
2	Photo	D	0.538	0.014	38.06	0.511	0.566
3	Powder	E	0.608	0.017	36.39	0.575	0.641
3	Powder	D	0.120	0.011	10.80	0.098	0.141
3	Photo	E	0.332	0.014	23.98	0.305	0.359
3	Photo	D	0.042	0.004	9.47	0.033	0.050

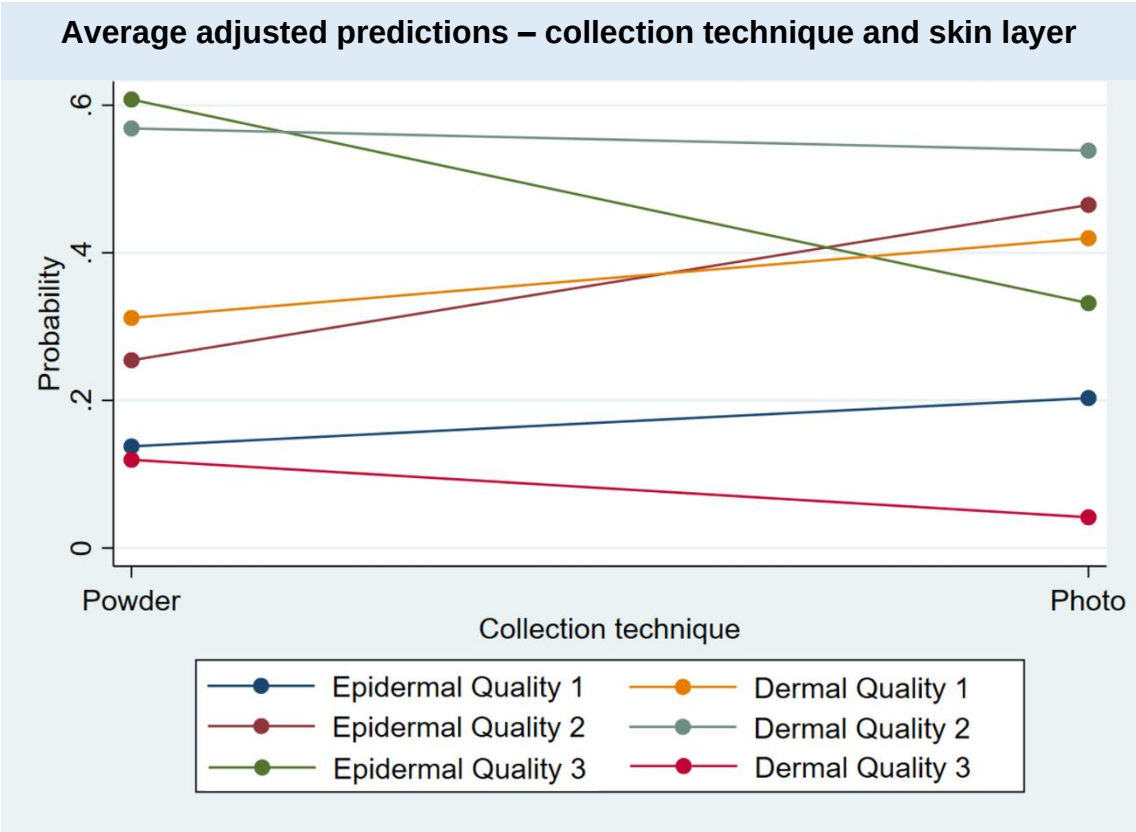

Figure 4.3.5 Average adjusted predictions of collection techniques for each quality category combined with the skin layer. Quality 1 – unsuitable for comparison, Quality 2 – suitable for manual comparison, Quality 3 – suitable for comparison using IDENT1 software (minimum of 8 minutiae detected).

4.3.1.2 Minutiae

One hundred and twenty fingerprints (60 epidermal and their 60 dermal counterparts) were analysed by the author for the number of minutiae and matching minutiae in a 1 cm^2 fingerprint area to also compare the quality of fingerprints quantitatively. Concordance correlation coefficients (ρ) for intra-observer agreement showed excellent agreement for minutiae counted in all three groups of fingerprint collection technique (pre-powder photography ρ = 0.985, post-powder photography ρ = 0.998, powder ρ = 0.992). Table 4.3.5, Table 4.3.6, and Table 4.3.7 present individual values and descriptive statistics for variables included in minutiae analysis of epidermal and dermal fingerprints collected using pre- and post-powder photography and black powder.

Table 4.3.5 Descriptive statistics for minutiae observed in fingerprints collected using pre-powder photography. E = epidermal, D = dermal, NA = not applicable

N	E minutiae	D minutiae	Matching minutiae (% coincidence)	Non-matching minutiae (% discrepancies)	E exclusive	D exclusive
1	12	0	0 (0.0%)	12 (100.0%)	12	0
2	3	0	0 (0.0%)	3 (100.0%)	3	0
3	13	1	1 (7.1%)	12 (92.9%)	12	0
4	0	0	0 (NA)	0 (NA)	0	0
5	0	7	0 (0.0%)	7 (100.0%)	0	7
6	25	1	0 (0.0%)	26 (100.0%)	25	1
7	0	1	0 (0.0%)	1 (100.0%)	0	1
8	0	0	0 (NA)	0 (NA)	0	0
9	6	0	0 (0.0%)	6 (100.0%)	6	0
10	17	0	0 (0.0%)	17 (100.0%)	17	0
11	1	1	0 (0.0%)	2 (100.0%)	1	1
12	9	5	1 (7.1%)	12 (92.9%)	8	4
13	2	8	1 (10.0%)	8 (10.0%)	1	7
14	6	2	0 (0.0%)	8 (100.0%)	6	2
15	0	0	0 (NA)	0 (NA)	0	0
16	2	0	0 (0.0%)	2 (100.0%)	2	0
17	9	1	0 (0.0%)	10 (100.0%)	9	1
18	1	0	0 (0.0%)	1 (100.0%)	1	0
19	0	2	0 (0.0%)	2 (100.0%)	0	2
20	0	0	0 (NA)	0 (NA)	0	0
Mean (+-SD)	5.3 (7)	1.5 (3.3)	0.2 (0.4) 1.5% (3.3)	6.5 (6.9) 98.5% (3.3)	5.2 (6.9)	1.3 (2.2)
Median	2	0.5	0	4.5	1.5	0
Min	0	0	0	0	0	0
Max	25	8	1	26	25	7

Table 4.3.6 Descriptive statistics for minutiae observed in fingerprints collected using powder. E = epidermal, D = dermal, NA = not applicable.

N	E minutiae	D minutiae	Matching minutiae (% coincidence)	Non-matching minutiae (% discrepancies)	E exclusive	D exclusive
1	0	0	0 (NA)	0 (NA)	0	0
2	0	1	0 (0.0%)	1 (100.0%)	0	1
3	12	2	2 (14.3%)	10 (85.7%)	10	0
4	0	2	0 (0.0%)	2 (100.0%)	0	2
5	7	3	0 (0.0%)	10 (100.0%)	7	3
6	24	2	2 (7.7%)	22 (92.3%)	22	0
7	4	1	0 (0.0%)	5 (100.0%)	4	1
8	0	1	0 (0.0%)	1 (100.0%)	0	1
9	6	9	1 (6.7%)	13 (93.3%)	5	8
10	35	3	3 (7.9%)	32 (92.1%)	32	0
11	8	7	2 (13.3%)	11 (86.7%)	6	5
12	29	16	12 (26.7%)	21 (73.3%)	17	4
13	12	10	7 (31.8%)	8 (68.2%)	5	3
14	25	8	2 (6.1%)	29 (93.9%)	23	6
15	7	2	0 (0.0%)	9 (100.0%)	7	2
16	6	3	0 (0.0%)	9 (100.0%)	6	3
17	17	6	4 (17.4%)	15 (82.6%)	13	2
18	11	0	0 (0.0%)	11 (100.0%)	11	0
19	8	10	2 (11.1%)	14 (88.9%)	6	8
20	0	0	0 (NA)	0 (NA)	0	0
Mean (+-SD)	10.6 (10.4)	4.3 (4.4)	1.9 (3) 7.9% (9.7)	11.2 (9.2) 92.7% (9.2)	8.7 (8.8)	2.5 (2.6)
Median	7.5	2.5	0.5	10	6.000	2
Min.	0	0	0	0	0	0
Max.	35	16	12	32	32	8

Table 4.3.7 Descriptive statistics for minutiae observed in fingerprints collected using post-powder photography. E = epidermal, D = dermal, NA = not applicable.

N	E minutiae	D minutiae	Matching minutiae (% coincidence)	Non-matching minutiae (% discrepancies)	E exclusive	D exclusive
1	6	4	3 (30.0%)	4 (70.0%)	3	1
2	3	1	0 (0.0%)	4 (100.0%)	3	1
3	8	1	0 (0.0%)	9 (100.0%)	8	1
4	0	3	0 (0.0%)	3 (100.0%)	0	3
5	0	7	0 (0.0%)	7 (100.0%)	0	7
6	25	0	0 (0.0%)	25 (100%)	25	0
7	0	0	0 (NA)	0 (NA)	0	0
8	0	0	0 (NA)	0 (NA)	0	0
9	10	12	3 (13.6%)	16 (86.4%)	7	9
10	18	5	3 (13.0%)	17 (87.0%)	15	2
11	0	3	0 (0.0%)	3 (100.0%)	0	3
12	13	3	1 (6.3%)	14 (93.8%)	12	2
13	2	10	1 (8.3%)	10 (91.7%)	1	9
14	19	6	5 (20.0%)	15 (80.0%)	14	1
15	7	0	0 (0.0%)	7 (100.0%)	7	0
16	3	0	0 (0.0%)	3 (100.0%)	3	0
17	8	3	0 (0.0%)	11 (100.0%)	8	3
18	10	6	4 (25.0%)	8 (75.0%)	6	2
19	0	5	0 (0.0%)	5 (100.0%)	0	5
20	8	0	0 (0.0%)	8 (100.0%)	8	0
Mean (+-SD)	7 (7.2)	3.5 (3.5)	1 (1.6) 6.5% (9.8)	8.5 (6.4) 93.5% (9.8)	6 (6.6)	2.5 (2.9)
Median	6.5	3	0	7.5	4.5	1.5
Min.	0	0	0	0	0	0
Max.	25	12	5	25	25	9

The total number of minutiae observed per area of interest in each of the skin layers and collection techniques are presented in Figure 4.3.6. Kolmogorov-Smirnov tests indicate that the total number of minutiae on epidermal and dermal fingerprints collected using post-powder photography follow a normal distribution ($D = 0.167$, $p = 0.145$ for epidermal fingerprints, $D = 0.161$, $p = 0.184$ for dermal fingerprints). Kolmogorov-Smirnov tests indicate that the total number of minutiae

on epidermal and dermal fingerprints do not follow normal distribution in pre-powder photography ($D = 0.233$, $p = 0.006$ for epidermal fingerprints, $D = 0.325$, $p < 0.001$ for dermal fingerprints) and powder ($D = 0.197$, $p = 0.041$ for epidermal fingerprints, $D = 0.267$, $p = 0.001$ for dermal fingerprints). The total number of minutiae observed on epidermal fingerprints is higher (median values for pre-powder photography, post-powder photography, and powder = 2, 7.5, 6.5 respectively) than the total number of minutiae observed on dermal fingerprints (median values for pre-powder photography, post-powder photography, and powder = 0.5, 2.5, 3 respectively) regardless of the collection technique utilised. However, according to the results of the paired t-test, there is no statistically significant difference between the total number of minutiae observed on epidermal and dermal fingerprints collected using post-powder photography ($t = 2.005$, $p = 0.059$). Sign tests could not be applied to compare the total number of minutiae between epidermal and dermal fingerprints collected with pre-powder photography and powder due to small sample sizes. Therefore, exact tests for binomial distribution were performed in both cases. The results suggest there is no statistically significant difference between the number of minutiae observed on epidermal and dermal fingerprints collected using pre-powder photography ($p = 0.118$) and black powder ($p = 0.096$).

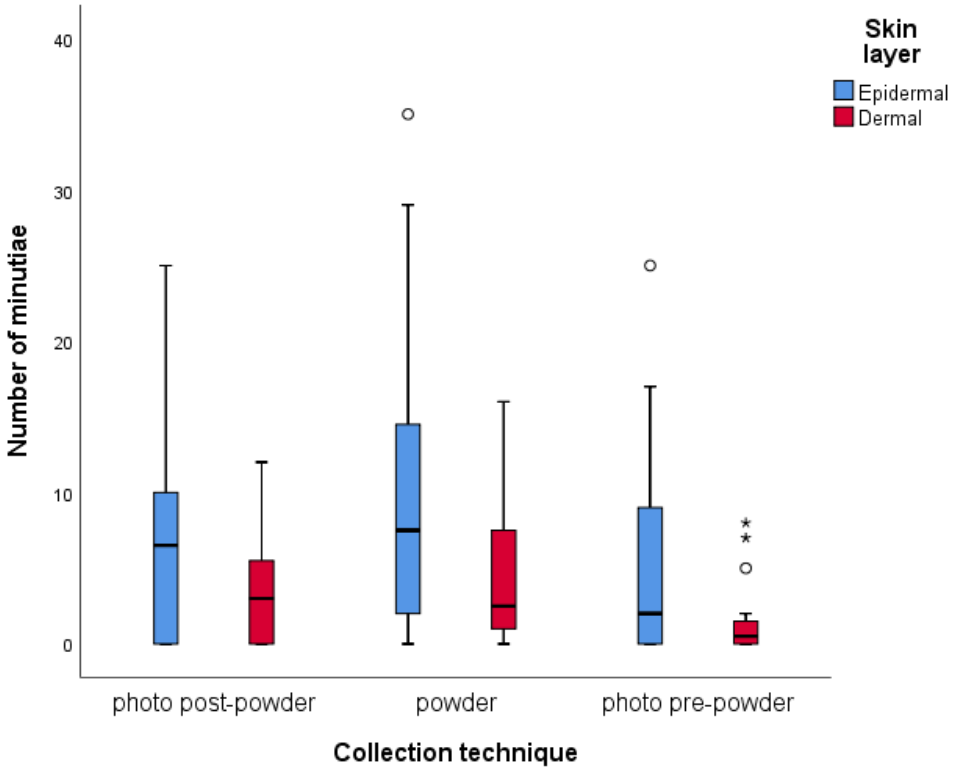

Figure 4.3.6 Minutiae counts observed per 1 cm^2 of epidermal and dermal fingerprints collected using powder, and pre- and post-powder photography.

Figure 4.3.7 shows the numbers of observed minutiae for the three fingerprint collection techniques with both epidermal and dermal fingerprints pooled. The results of the Friedman test suggest there is a statistically significant difference between the numbers of minutiae observed on fingerprints collected using the three collection techniques ($X^2 = 17.92$, $p < 0.001$). The results of a subsequent series of sign tests show that there is a statistically significant difference between the number of minutiae observed on fingerprints collected using black powder and pre-powder photography ($Z = -3.71$, $p < 0.001$), as well as post-powder and pre-powder photography ($Z = -2.16$, $p = 0.031$). No statistically significant difference was observed between the number of minutiae observed on fingerprints collected using powder and post-powder photography ($Z = -1.89$, $p = 0.059$).

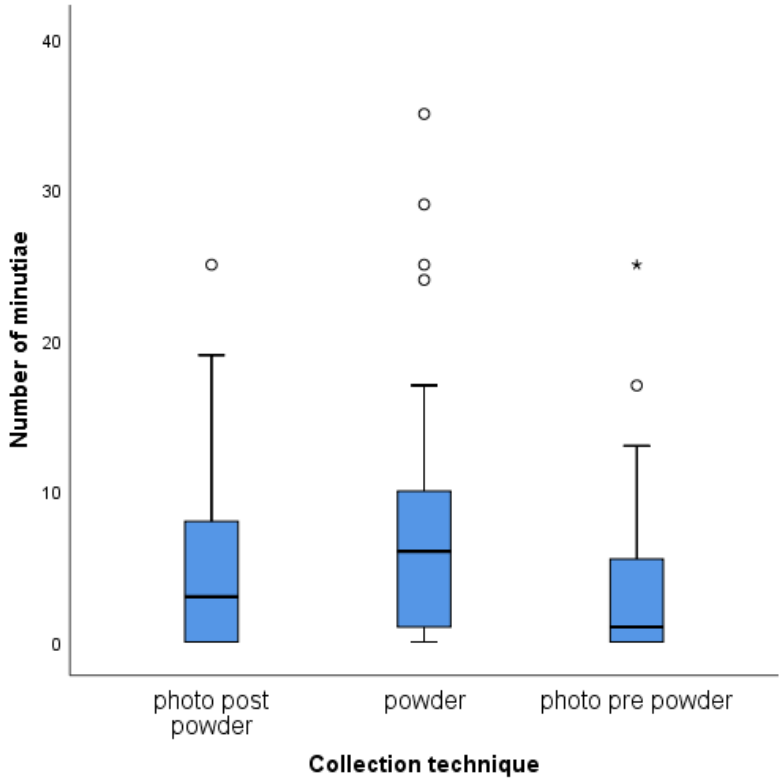

Figure 4.3.7 Minutiae counts observed per 1 cm^2 of fingerprints (epidermal and dermal pooled) grouped by collection techniques.

The number of matching minutiae observed per area of interest for each of the collection techniques are presented in Figure 4.3.8. Kolmogorov-Smirnov tests indicate that the numbers of matching minutiae on fingerprints collected using the three collection techniques do not follow a normal distribution ($D = 0.381$, $p < 0.001$ for post-powder photography, $D = 0.509$, $p < 0.001$ for pre-powder photography, $D = 0.208$, $p < 0.001$ for powder). The results of the Friedman test suggest there is a statistically significant difference between the number of matching minutiae observed in fingerprints collected using the three collection techniques ($X^2 = 9.385$, $p = 0.009$). Due to small sample size a sign test could not be applied, and a series of exact tests for binomial distribution were performed instead to test for statistically significant differences between matching minutiae numbers of each fingerprint collection technique category. A statistically significant difference was found when comparing matching minutiae numbers of fingerprints collected using pre-powder photography and powder ($p = 0.002$). There is no statistical difference between the matching minutiae numbers of fingerprints collected using pre- and post-powder photography ($p = 0.219$) and post-powder photography and powder ($p = 0.549$). The numbers of matching compared to non-matching (found exclusively in epidermal and exclusively in

dermal fingerprints) minutiae observed per area of interest for each of the collection techniques are presented in Figure 4.3.9, Figure 4.3.10, and Figure 4.3.11. The number of matching minutiae was highest in epidermal-dermal fingerprint pairs collected using powder (Figure 4.3.10). In contrast, only one matching minutia was observed in each of the three epidermal-dermal fingerprint pairs collected using pre-powder photography (Figure 4.3.9).

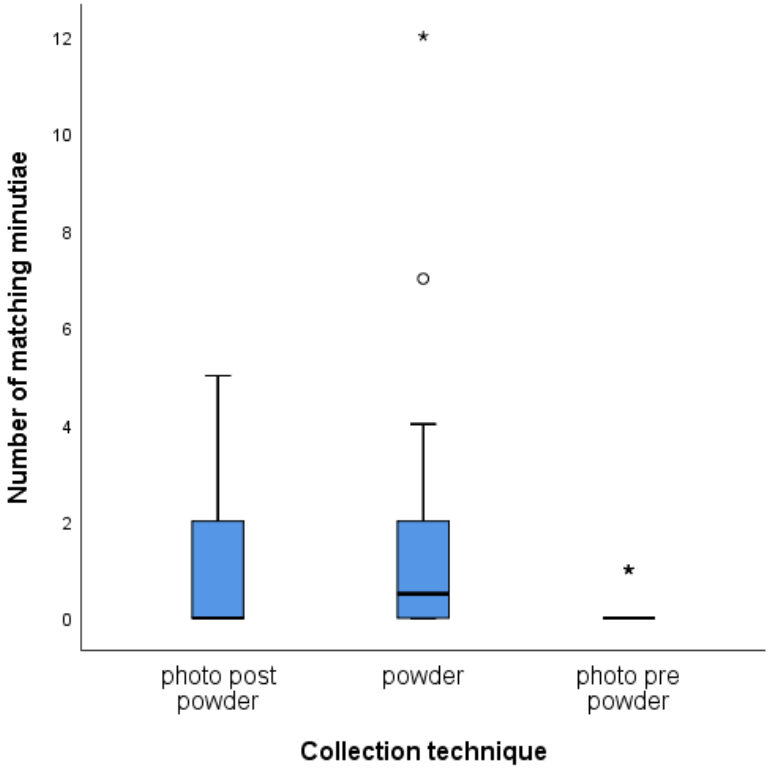

Figure 4.3.8 Matching minutiae observed per 1 cm^2 of fingerprints grouped by collection techniques.

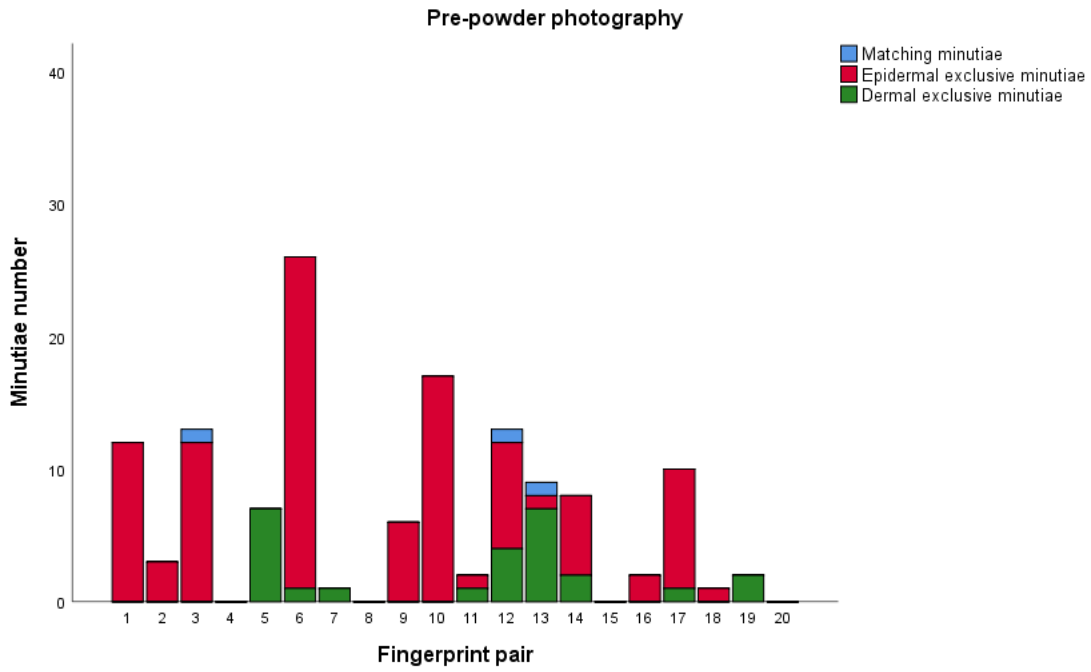

Figure 4.3.9 Matching and non-matching minutiae numbers observed on fingerprints collected using pre-powder photography.

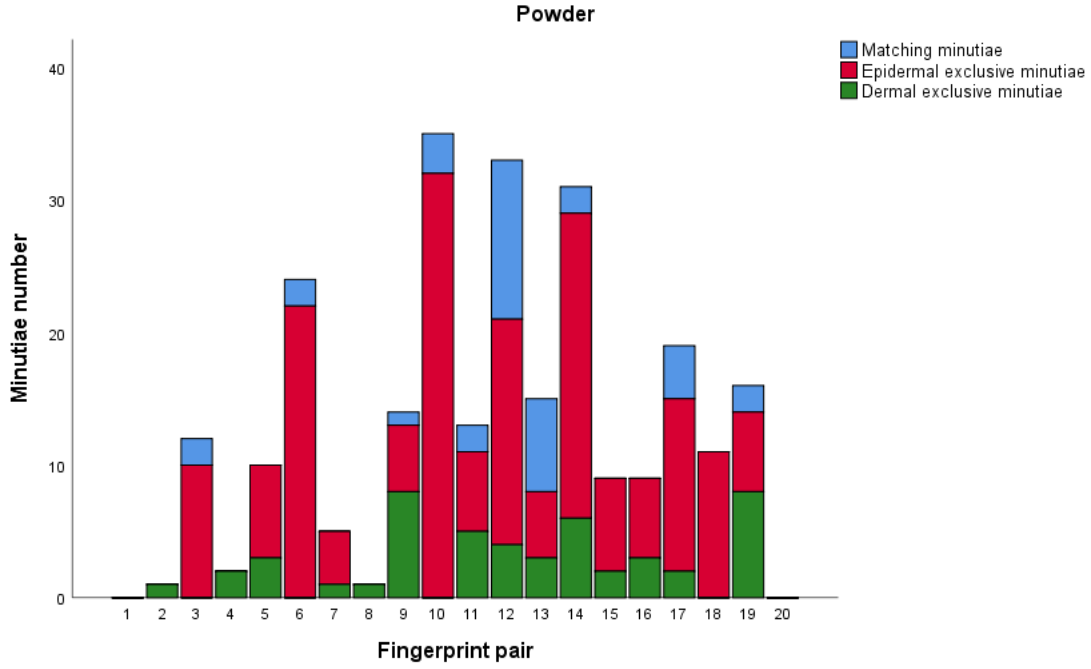

Figure 4.3.10 Matching and non-matching minutiae numbers observed on fingerprints collected using powder.

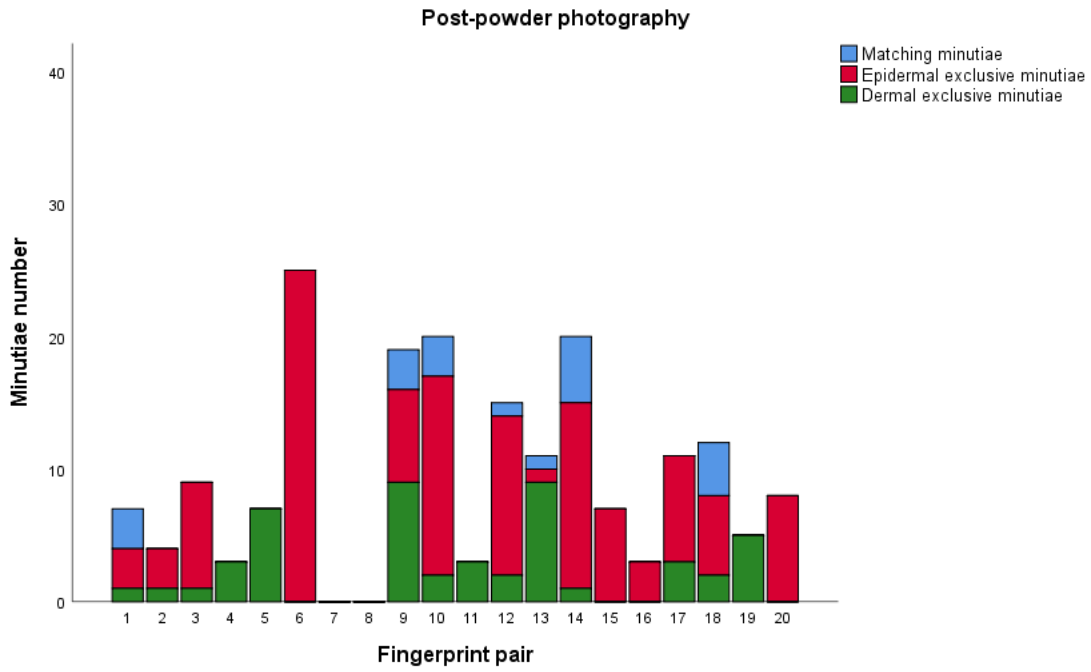

Figure 4.3.11 Matching and non-matching minutiae numbers observed on fingerprints collected using post-powder photography.

4.3.2 Expert fingerprint assessment and comparison

Fingerprint examiners from four countries were asked to assess quality, usability, and minutiae in epidermal and dermal fingerprints. The experts were also asked to compare epidermal-dermal fingerprint pairs. The total number of fingerprints analysed was 160 and they were organised into two groups of 40 epidermal-dermal fingerprint pairs grouped by powder and post-powder photography collection techniques. Half of the fingerprint pairs were matched (originating from the same digit) and the other half of the fingerprint pairs were unmatched.

The experts analysed a subsample of fingerprints collected using powder and post-powder photography due to the fingerprints collected using pre-powder photography being of lower quality than fingerprints from the other two groups (section 4.3.1.1).

4.3.2.1 Quality and usability

The experts were asked to assess the quality category and usability of each fingerprint from the dataset. The quality and usability standards vary for each group of experts according to the country they work in. The details of the quality and usability standards of each country are described in sections 4.2.3.3, 4.2.3.4,

4.2.3.5, and 4.2.3.6. Figure 4.3.12 shows the quality assessment of epidermal and dermal fingerprints performed by trained fingerprint examiners from Belgium. The number of fingerprints designated as category 3 (suitable for comparison and identification) is higher for prints recovered from the epidermal skin layer (average powder = 22.3, average post-powder photography = 18.5) compared to prints recovered from the dermal skin layer (average powder = 6.8, average post-powder photography = 6.5) regardless of collection technique for all Belgian experts. The number of epidermal fingerprints assigned to category 3 is higher for powder prints (average = 22.3) compared to post-powder photography prints (average = 18.5) for all Belgian experts. The number of dermal fingerprints designated as category 3 is one or two prints higher for post-powder photography prints compared to powder prints for experts H, I, and O; the opposite is observed in expert N. The number of fingerprints designated as category 2 (suitable for comparison but not for identification) is higher for prints recovered from the dermal skin layer (average powder = 13.5, average post-powder photography = 13.3) compared to prints recovered from the epidermal skin layer (average powder = 6.3, average post-powder photography = 7) regardless of collection technique for all Belgian experts. There is no clear trend for the number of epidermal fingerprints assigned to category 2 when comparing powder prints to post-powder photography prints. The number of dermal fingerprints designated as category 2 is two to three prints higher for powder prints compared to post-powder photography prints for experts H, I, and O; the opposite is observed in expert N. The number of fingerprints assigned to category 1 (unsuitable for comparison) is equal (expert O – post-powder photography fingerprints) or higher for prints recovered from the dermal skin layer (average powder = 19.8, average post-powder photography = 20.3) compared to prints recovered from the epidermal skin layer (average powder = 11.5, average post-powder photography = 14.5) for Belgian experts. The number of both epidermal and dermal fingerprints designated as category 1 is greater for post-powder photography prints compared to powder prints for experts H, I, and O; the opposite is observed in expert N.

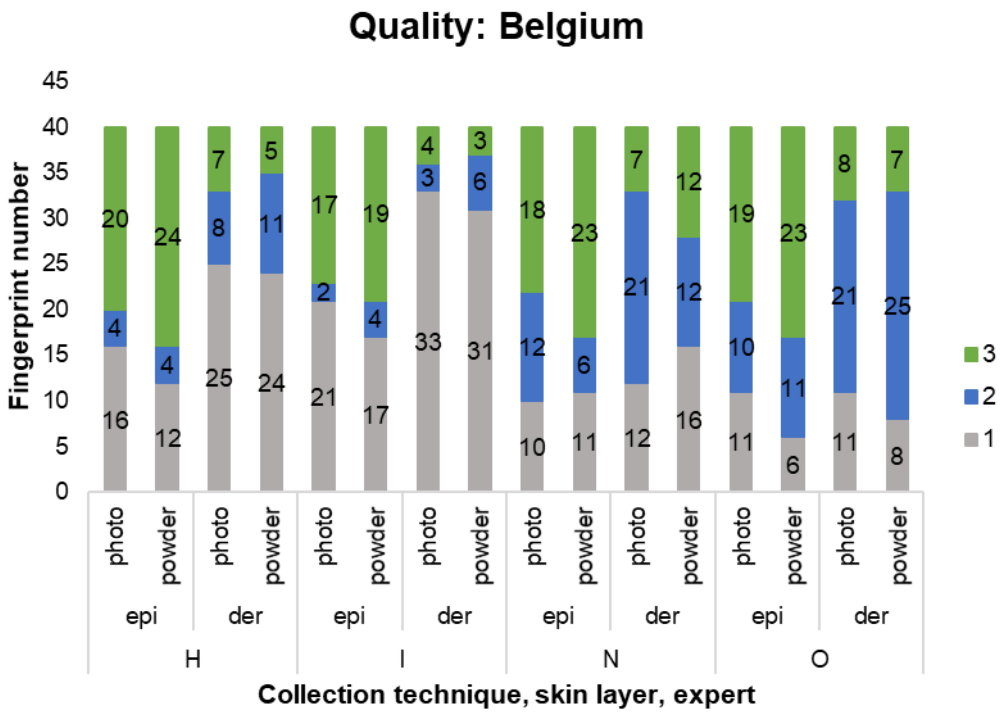

Figure 4.3.12 Quality assessment of fingerprints performed by trained fingerprint examiners from Belgium. Quality categories: 1 – less than 8 minutiae/unsuitable for comparison, 2 – between 8 and 11 minutiae/suitable for comparison but not for identification, 3 – 12 or more minutiae/suitable for comparison and identification. epi = epidermal skin layer, der = dermal skin layer.

Figure 4.3.13 shows the quality assessment of epidermal and dermal fingerprints performed by trained fingerprint examiners from the UK. The number of fingerprints designated as category 3 (suitable for comparison using IDENT1 software) is higher for prints recovered from the epidermal skin layer (average powder = 22.1, average post-powder photography = 21) compared to prints recovered from the dermal skin layer (average powder = 7.1, average post-powder photography = 7.5) regardless of collection technique for all UK experts. The number of both epidermal and dermal fingerprints assigned to category 3 is higher for powder prints (average epidermal = 25.6, average dermal = 8.8) compared to post-powder photography prints (average epidermal = 20.6, average dermal = 6.8) for all UK experts who analysed the full fingerprint dataset. The number of fingerprints designated as category 2 (suitable for manual comparison) is higher for prints recovered from the dermal skin layer (average powder = 12.8, average post-powder photography = 13) compared to prints recovered from the epidermal skin layer (average powder = 7.4, average post-powder photography = 6.6) regardless of collection technique for all UK experts who

analysed an equal number of powder and post-powder photography fingerprints except for the expert B (powder fingerprints). The number of epidermal fingerprints designated as category 2 is greater for powder prints compared to post-powder photography prints for experts A, B, D, and Q; the opposite is observed in expert C. The experts E and F cannot be compared due to unequal numbers of analysed fingerprints within collection technique grouping. There is no clear trend for the number of epidermal fingerprints assigned to category 2 when comparing powder prints to post-powder photography prints analysed by UK experts who completed the analysis of the full dataset. The number of fingerprints assigned to category 1 (unsuitable for comparison) is equal (expert Q – post-powder photography fingerprints) or higher for prints recovered from the dermal skin layer (average powder = 14.7, average post-powder photography = 19.2) compared to prints recovered from the epidermal skin layer (average powder = 5.7, average post-powder photography = 12.5) for UK experts. The number of epidermal fingerprints designated as category 1 is higher for post-powder photography prints (average = 12.8) compared to powder prints average = 7) for all UK experts who analysed the full fingerprint dataset. The number of dermal fingerprints designated as category 1 is greater for post-powder photography prints compared to powder prints for UK experts C, D, and Q; the opposite is observed in experts A and B. The experts E and F cannot be compared due to unequal numbers of analysed fingerprints within collection technique grouping.

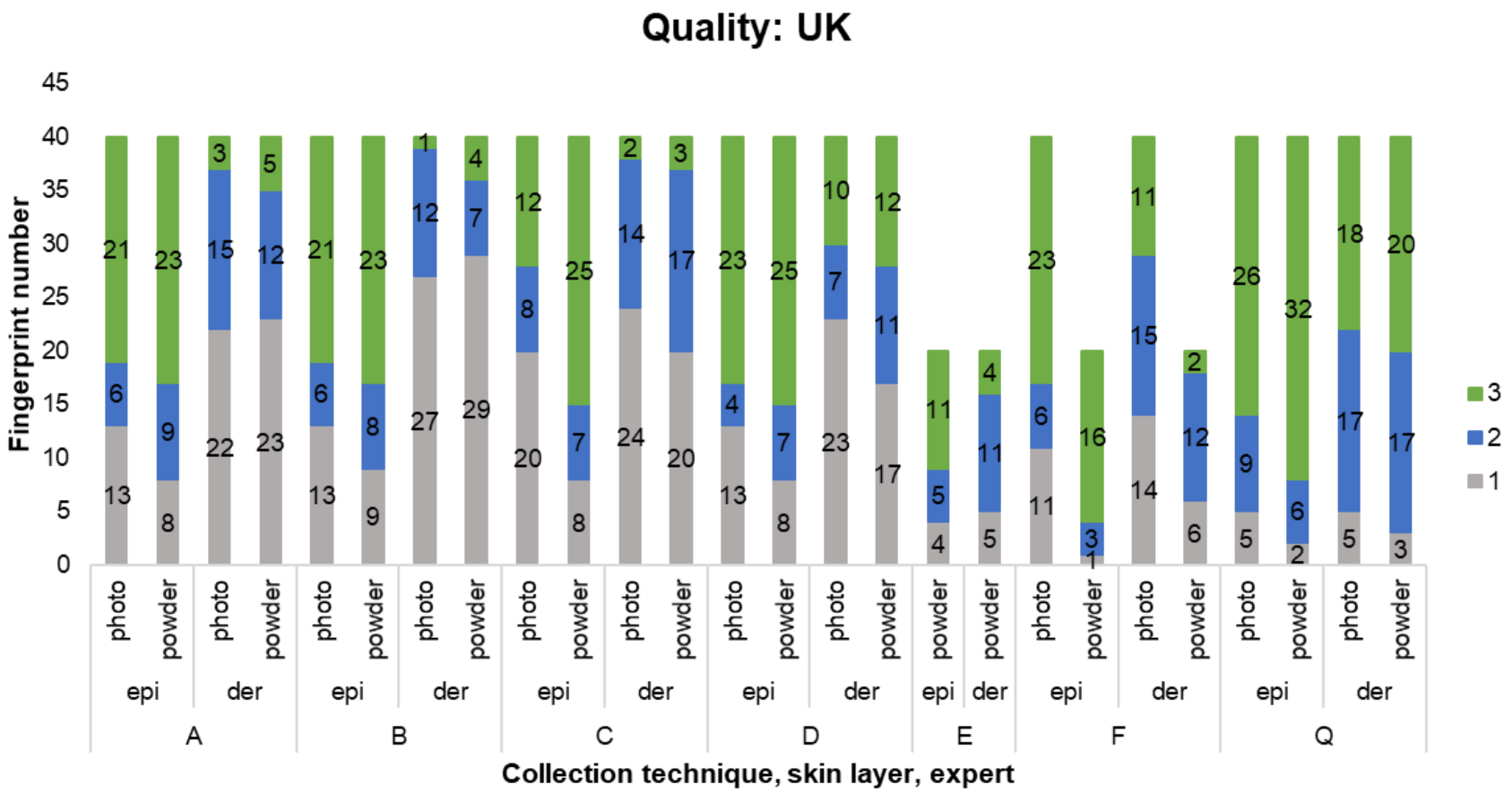

Figure 4.3.13 Quality assessment of fingerprints performed by trained fingerprint examiners from the UK. Quality categories: 1 – unsuitable for comparison, 2 – suitable for manual comparison, 3 – suitable for comparison using IDENT1 software (minimum of 8 minutiae detected). epi = epidermal skin layer, der = dermal skin layer.

Figure 4.3.14 shows the quality assessment of epidermal and dermal fingerprints performed by trained fingerprint examiners from Sweden. The number of fingerprints designated as category 2 + 3 (suitable for comparison) is higher for prints recovered from the epidermal skin layer (powder average = 20.3, post-powder photography expert J = 23) compared to prints recovered from the dermal skin layer (powder average = 13, post-powder photography expert J = 17) regardless of collection technique for all Swedish experts. The number of both epidermal and dermal fingerprints assigned to category 2 + 3 is higher for powder prints (epidermal = 32, dermal = 22) compared to post-powder photography prints (epidermal = 23, dermal = 17) for expert J who as the only one from among the Swedish experts analysed the full fingerprint dataset. The number of fingerprints assigned to category 1 (unsuitable for comparison) is higher for powder prints recovered from the dermal skin layer (average = 14.8) compared to powder prints recovered from the epidermal skin layer (average = 7.5) for Swedish experts. The number of epidermal and dermal fingerprints designated as category 1 is higher for post-powder photography prints (epidermal = 17, dermal = 23) compared to powder prints (epidermal = 8, dermal = 18) for expert J who analysed the full fingerprint dataset.

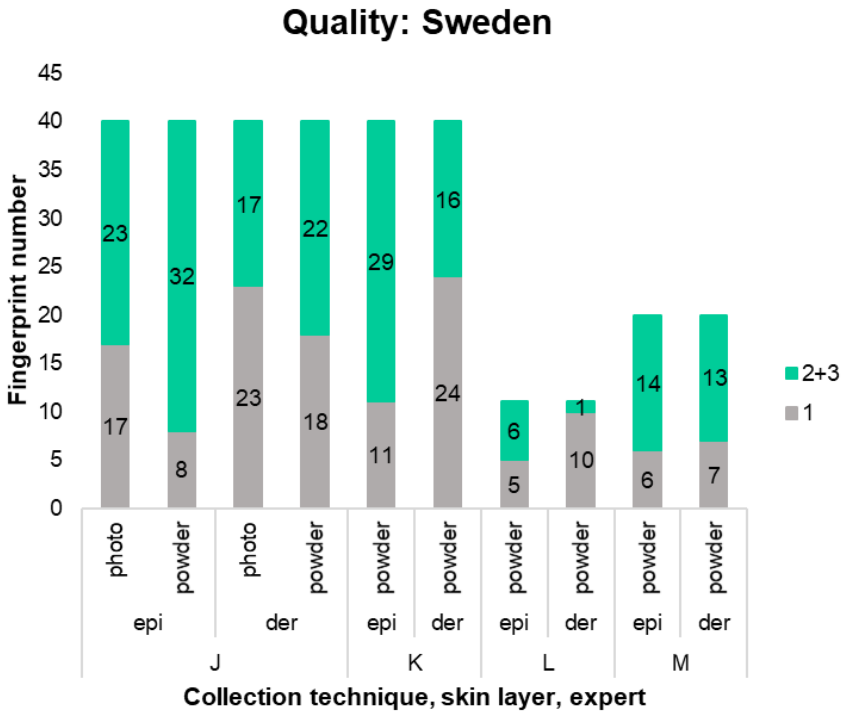

Figure 4.3.14 Quality assessment of fingerprints performed by trained fingerprint examiners from Sweden. Quality categories: 1 – unsuitable for comparison, 2+3 – suitable for comparison. epi = epidermal skin layer, der = dermal skin layer.

Figure 4.3.15 shows the quality assessment of epidermal and dermal fingerprints performed by trained fingerprint examiner from New Zealand. The number of fingerprints designated as category 3 (suitable for comparison with AFIS employed by New Zealand police) is higher for prints recovered from the epidermal skin layer (powder = 29, post-powder photography = 25) compared to prints recovered from the dermal skin layer (powder = 17, post-powder photography = 18) regardless of collection technique. The number of epidermal fingerprints assigned to category 3 is higher for powder prints (n = 29) compared to post-powder photography prints (n = 25). The number of dermal fingerprints assigned to category 3 is higher for post-powder photography prints (n = 18) compared to powder photography prints (n = 17). The number of fingerprints designated as category 2 (suitable for manual comparison) is higher for powder prints recovered from the dermal skin layer (n = 9) compared to powder prints recovered from the epidermal skin layer (n = 5) and equal for post-powder photography epidermal and dermal prints (n = 8). The number of fingerprints assigned to category 1 (unsuitable for comparison) is higher for prints recovered from the dermal skin layer (powder = 14, post-powder photography = 14) compared to prints recovered from the epidermal skin layer (powder = 6, post-powder photography = 7). The number of epidermal fingerprints designated as category 1 is one fingerprint higher for post-powder photography prints compared to powder prints. The number of dermal fingerprints designated as category 1 is equal for both fingerprint collection techniques.

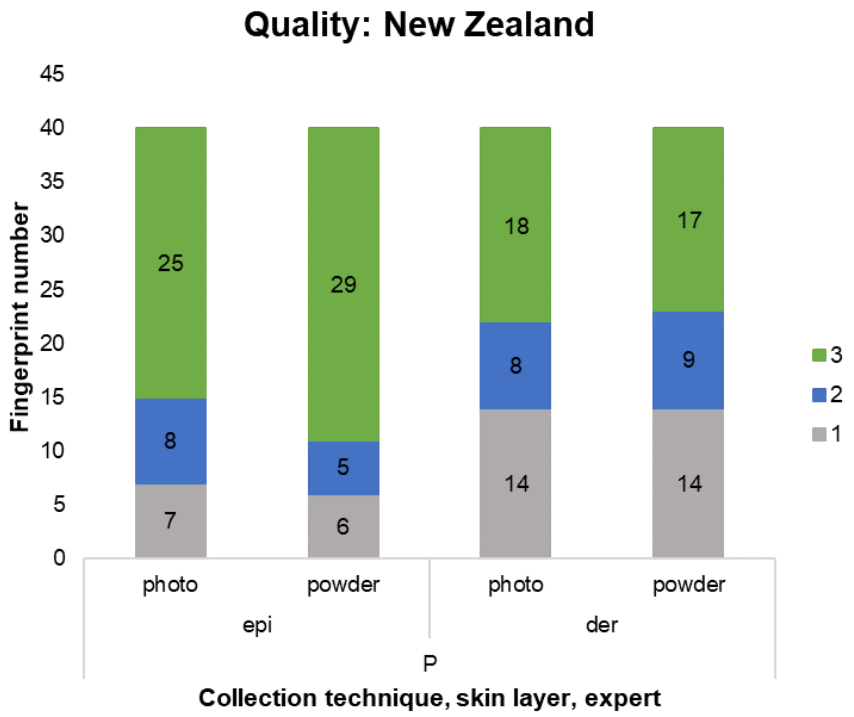

Figure 4.3.15 Quality assessment of fingerprints performed by trained fingerprint examiner from New Zealand. Quality categories: 1 – unsuitable for comparison, 2 – suitable for manual comparison, 3 – suitable for comparison using AFIS software (minimum of 6 minutiae detected). epi = epidermal skin layer, der = dermal skin layer.

Since the standards of fingerprint quality assessment differ between countries (section 4.2.3), the reliability coefficients for inter-rater agreement measurements were calculated separately for the UK (n = 5, those who completed the analysis of the full dataset) and Belgian fingerprint experts. There was only one expert from Sweden who completed the analysis of the full dataset and one from New Zealand, so the inter-rater reliability calculation within that group was not possible. Table 4.3.8, Figure 4.3.16, and Figure 4.3.17 show the Krippendorff alpha reliability coefficients and their bootstrapped means and 95% confidence intervals for fingerprint quality assessment performed by the UK and Belgian examiners.

Table 4.3.8 Krippendorff alpha coefficients (α) for fingerprint quality assessment performed by fingerprint examiners from Belgium and examiners from the UK who completed analysis of the full dataset. Values** considered reliable (α ≥ 0.8). Values* with 95% confidence interval containing α ≥ 0.8.[2]

Country (number of experts)	Epidermal (n = 80)	Dermal (n = 80)	Powder (n = 80)	Photo (n = 80)
BE (n = 4)	0.752*	0.362	0.655	0.606
UK (n = 5)	0.685	0.424	0.686	0.551
UK (n = 4)	0.730*	0.600	0.816**	0.637

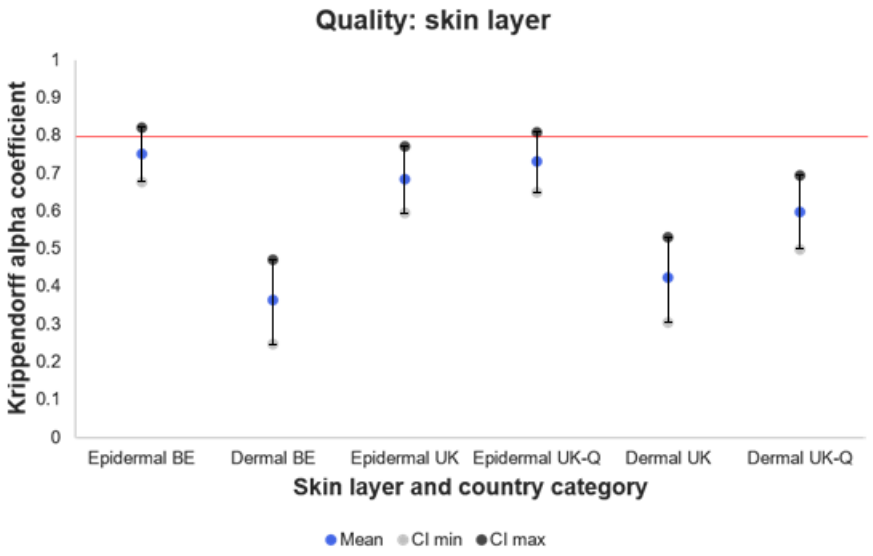

Figure 4.3.16 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for quality assessment of epidermal and dermal fingerprints performed by fingerprint examiners from Belgium and examiners from the UK who completed analysis of the full dataset. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[3]

[2] 'UK (n = 4)' represents the UK experts without the expert Q.
[3] UK-Q indicates coefficients for four UK experts without the assessment of expert Q.

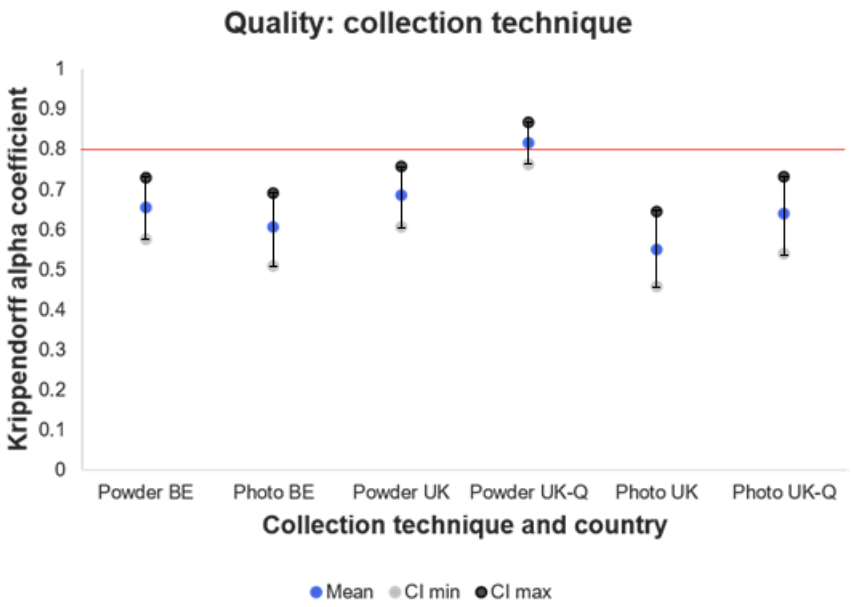

Figure 4.3.17 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for quality assessment of fingerprints collected using post-powder photography and black powder performed by fingerprint examiners from Belgium and examiners from the UK who completed analysis of the full dataset. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[4]

Sufficient agreement between the experts (α ≥ 0.8) was found only in the case of the four UK examiners (all UK examiners without the examiner Q, calculated due to the differences in equipment used by the expert Q during fingerprint analysis) analysing fingerprints collected using powder (Table 4.3.8). However, after calculating 95% confidence intervals of bootstrapped coefficient values, the reliability coefficient interval for quality of epidermal fingerprints assessed by four UK and all Belgian examiners contained α values equal to or greater than 0.8 (Figure 4.3.16, Figure 4.3.17), meaning sufficient inter-rater agreement when analysing quality assessment data within these two variables cannot be ruled out. Reliability coefficients from Table 4.3.8 have higher values for quality assessment of epidermal fingerprints in comparison to dermal fingerprints and higher values of quality assessment for fingerprints collected using powder than in fingerprints collected using post-powder photography. Lack of overlap in 95% confidence interval ranges of epidermal and dermal fingerprint quality assessments performed by all UK and Belgian experts suggests there is a statistically supported difference between the inter-rater agreements when assessing the

[4] 'UK-Q' indicates coefficients for four UK experts without the assessment of expert Q.

quality of epidermal and dermal fingerprints (Figure 4.3.16). Similar lack of overlap in 95% confidence interval ranges, in this case only of quality assessment of powder and post-powder photography fingerprints performed by four UK experts (without expert Q), suggests there is a statistically supported difference between the inter-rater agreements when assessing the quality of fingerprints collected using powder and post-powder photography performed by the four UK experts (Figure 4.3.17).

Table 4.3.9, Figure 4.3.18, and Figure 4.3.19 show the resulting Krippendorff alpha reliability coefficients and their bootstrapped means and 95% confidence intervals for fingerprint quality assessment performed by the five trained UK fingerprint examiners who completed the analysis of the full dataset compared with the baseline assessment undertaken by the author who is not trained in fingerprint examination.

Table 4.3.9 Krippendorff alpha coefficients (α) for fingerprint quality assessment comparing outcomes of each UK fingerprint examiners who completed analysis of the full dataset to baseline assessment. Values* with 95% confidence interval containing α ≥ 0.8.

UK Expert	Epidermal (n = 80)	Dermal (n = 80)	Powder (n = 80)	Photo (n = 80)
A	0.776*	0.438	0.753*	0.622
B	0.774*	0.211	0.701	0.564
C	0.615	0.347	0.770*	0.236
D	0.747*	0.508	0.769*	0.571
Q	0.632	0.308	0.552	0.492

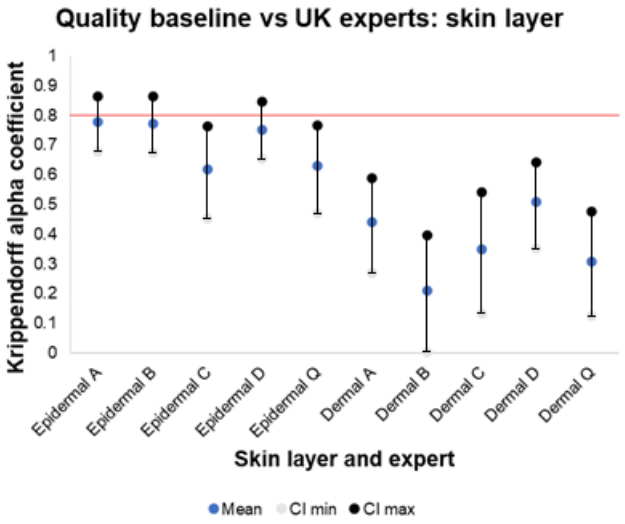

Figure 4.3.18 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for quality assessment of epidermal and dermal fingerprints comparing outcomes of each UK fingerprint examiner who completed analysis of the full dataset to baseline assessment. The red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.

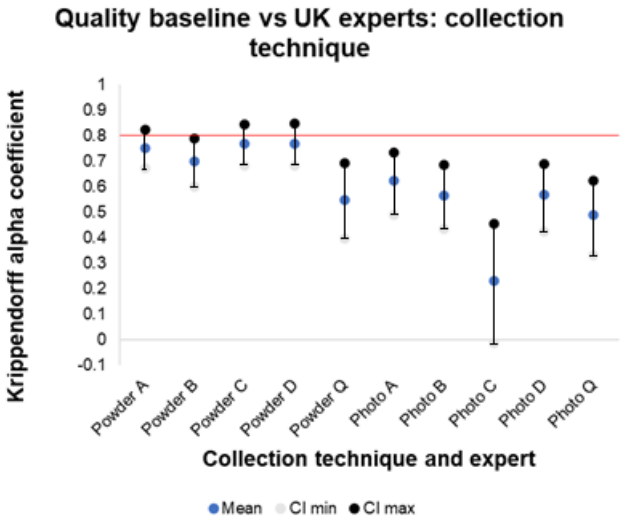

Figure 4.3.19 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for quality assessment of fingerprints collected using post-powder photography and black powder comparing outcomes of each UK fingerprint examiner who completed analysis of the full dataset to baseline assessment. The red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.

Regardless of the skin layer and collection technique, all α values between the trained fingerprint examiners and the author were below 0.8, which are values below the threshold of sufficient inter-rater agreement (Table 4.3.9). However, sufficient inter-rater agreement (where α ≥ 0.8) for some cases of reliability

coefficients from Table 4.3.9 cannot be ruled out for 95% confidence intervals of bootstrapped coefficient values which include the values equal to or greater than 0.8. This was the case for the reliability coefficient 95% confidence intervals of epidermal fingerprints quality assessed by the author and experts A, B, C, and for powder fingerprint quality assessed by the author and experts A, C, D, which all contain α values equal to or greater than 0.8 (Figure 4.3.18, Figure 4.3.19). Reliability coefficients from Table 4.3.9 have higher values for quality assessment of epidermal fingerprints when compared to dermal fingerprints and higher values of quality assessment in fingerprints collected using powder (between 0.615 and 0.776) than in fingerprints collected using post-powder photography (between 0.211 and 508). However, a lack of overlap in 95% confidence interval ranges of epidermal and dermal fingerprint quality assessments, was observed only between the baseline assessor and UK experts A, B, and D (Figure 4.3.18). There was only one case of statistically supported difference between the inter-rater agreements of fingerprints collected using powder and post-powder photography; the lack of overlap in 95% confidence interval ranges of powder and photography fingerprint quality assessments was observed only between the baseline assessor and UK experts C (Figure 4.3.19).

Usability was extrapolated from quality assessment where fingerprints with category 2 and 3 quality were pooled and re-categorised as usable and quality 1 fingerprints re-categorised as unusable. Table 4.3.10 shows the number of experts agreeing on the usability assessment of fingerprints grouped by skin layer and collection technique. The experts who completed the analysis of the full dataset from different countries were pooled to summarise the overall usability of a fingerprint. The highest number of usable fingerprints in which all 11 experts agree was observed for epidermal fingerprints collected using powder; the experts agreed on more than half of the sample of fingerprints from this category (23 out of 40) as being usable. All 11 experts agreed on 12 epidermal fingerprints collected using post-powder photography as being usable, which is almost a half of fingerprints less than epidermal fingerprints collected using photography and more than ⅓ of the whole sample of epidermal fingerprints collected using photography.

Table 4.3.10 Experts' agreement on the usability of fingerprints split by skin layer and fingerprint collection technique. Only the experts who completed analysis of the full dataset were included.

Number of experts assigning to 'usable'	Number of fingerprints			
	Epidermal		Dermal	
	Powder	Photo	Powder	Photo
11 / 11	23	12	5	3
10 / 11	2	9	4	6
9 / 11	4	1	5	2
8 / 11	1	2	3	3
7 / 11	1	2	3	2
6 / 11	0	1	3	4
5 / 11	2	2	1	3
4 / 11	0	1	0	2
3 / 11	2	2	4	4
2 / 11	2	3	6	5
1 / 11	1	1	5	3
0 / 11	2	4	1	3
Total	40	40	40	40

All 11 experts agreed on 5 dermal fingerprints collected using powder being usable, which is 1/8 of the whole sample of dermal fingerprints collected using powder. All 11 experts agreed on 3 dermal fingerprints collected using post-powder photography being usable, which is more than 1/13 of the whole sample of fingerprints collected using this technique. When comparing the numbers of epidermal and dermal fingerprints which all experts deemed usable, the number of epidermal fingerprints collected using powder was over four times the number of dermal fingerprints collected in this way, and the number of epidermal fingerprints collected using photography was exactly four times the number of dermal fingerprints collected using this method. All 11 experts agreed that two epidermal and one dermal fingerprint collected using powder were unusable, and four epidermal and three dermal fingerprints collected using post-powder photography were unusable.

Table 4.3.11, Figure 4.3.20, and Figure 4.3.21 show the resulting Krippendorff alpha reliability coefficients and their bootstrapped means and 95% confidence intervals for fingerprint usability assessment performed by the UK and Belgian examiners separately and for all experts pooled into one group. Only the experts who completed the analysis of the full dataset were included in the calculations.

Table 4.3.11 Krippendorff alpha coefficients (α) for fingerprint usability assessment performed by fingerprint examiners. Values* with 95% confidence interval containing α ≥ 0.8.[5]

Country (number of experts)	Epidermal (n = 80)	Dermal (n = 80)	Powder (n = 80)	Photo (n = 80)
BE (n = 4)	0.602	0.234	0.427	0.420
UK (n = 5)	0.571	0.355	0.539	0.418
UK (n = 4)	0.685*	0.561	0.744*	0.554
UK + BE + SWE + NZ (n = 11)	0.577	0.378	0.514	0.463
UK + BE + SWE + NZ (n = 10)	0.615*	0.434	0.576	0.503

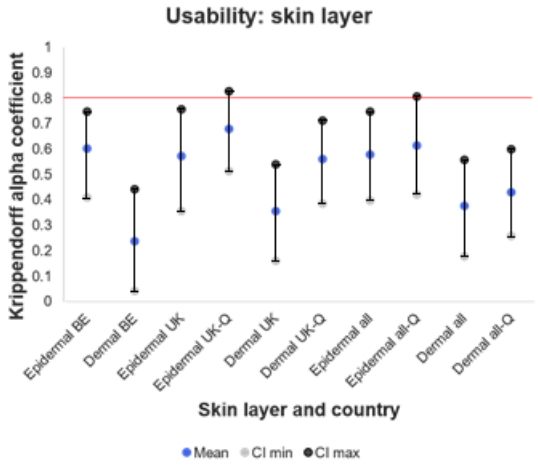

Figure 4.3.20 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for usability assessment of epidermal and dermal fingerprints performed by fingerprint examiners. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[6]

[5] 'UK (n = 4)' represents the UK experts who completed the analysis of full dataset without the expert Q. 'UK + BE + SWE + NZ (n = 10)' represents the experts who completed the analysis of full dataset without the expert Q.

[6] 'UK-Q' and 'all-Q' indicates coefficients for experts of given country/ies without the assessment of expert Q.

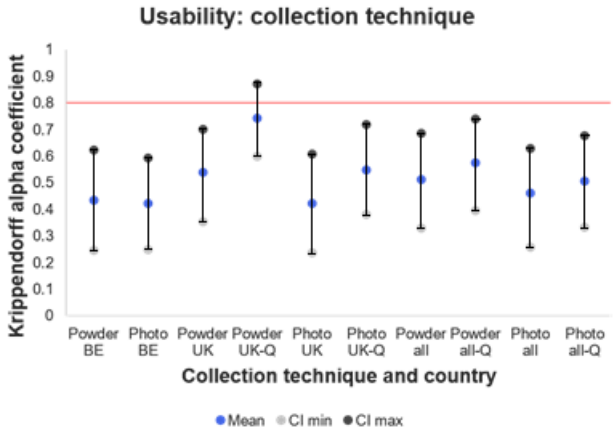

Figure 4.3.21 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for usability assessment of fingerprints collected using post-powder photography and black powder performed by fingerprint examiners. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[7]

No reliability coefficient value was found to suggest sufficient agreement (α ≥ 0.8) between the experts analysing the usability of fingerprints (Table 4.3.11). However, after calculating 95% confidence intervals of bootstrapped coefficient values, the reliability coefficient interval for the usability of epidermal and powder fingerprints assessed by four UK examiners, and usability of epidermal fingerprints assessed by all but examiner Q contained α values equal to or greater than 0.8 (Figure 4.3.20, Figure 4.3.21), meaning sufficient inter-rater agreement when analysing data in these three cases cannot be ruled out. Reliability coefficients from Table 4.3.11 have higher values for usability assessment of epidermal fingerprints when compared to dermal fingerprints and higher values of quality assessment of fingerprints collected using powder over fingerprints collected using post-powder photography. However, since there are overlaps in all cases of 95% confidence interval ranges of epidermal and dermal fingerprints usability assessment as well as in all cases of usability assessment of fingerprints collected using powder and post-powder photography, there was no statistically supported difference observed between the inter-rater agreements when assessing the usability of epidermal and dermal fingerprints, and fingerprints collected using powder and post-powder photography (Figure 4.3.20, Figure 4.3.21).

[7] 'UK-Q' and 'all-Q' indicates coefficients for experts of given country/ies without the assessment of expert Q.

4.3.2.2 Minutiae

Fingerprint examiners were asked to assess the numbers of minutiae on each analysed fingerprint. The procedures of fingerprint analysis and comparison differ between the countries with a numerical approach (in this case Belgium) and the countries which employ a non-numerical/holistic approach (in this case UK, Sweden, New Zealand) and the reporting of results in this section reflects these differences. Figure 4.3.22 and Table 4.3.12 show respectively the numbers and percentages of epidermal and dermal fingerprints collected using post-powder photography and powder categorised by the number of minutiae observed by Belgian trained fingerprint examiners. The experts from Belgium identified 12 or more minutiae on average in 52.5% of epidermal and 10.6% of dermal fingerprints collected using powder. The same number range of minutiae was identified by the same experts on average in 38.1% of epidermal and 10.6% of dermal fingerprints collected using post-powder photography. The experts from Belgium identified between 11 and 8 minutiae on average in 15% of epidermal and 29.4% of dermal fingerprints collected using powder. The same number range of minutiae was identified by the same experts on average in 12.5% of epidermal and 18.1% of dermal fingerprints collected using post-powder photography. The experts from Belgium identified 7 and fewer minutiae on average in 22.5% of epidermal and 40% of dermal fingerprints collected using powder. The same number range of minutiae was identified by the same experts on average in 33.8% of epidermal and 51.3% of dermal fingerprints collected using post-powder photography. The experts from Belgium identified no minutiae on average in 10% of epidermal and 20% of dermal fingerprints collected using powder. No minutiae were identified by Belgian experts on average in 15.6% of epidermal and 20% of dermal fingerprints collected using post-powder photography.

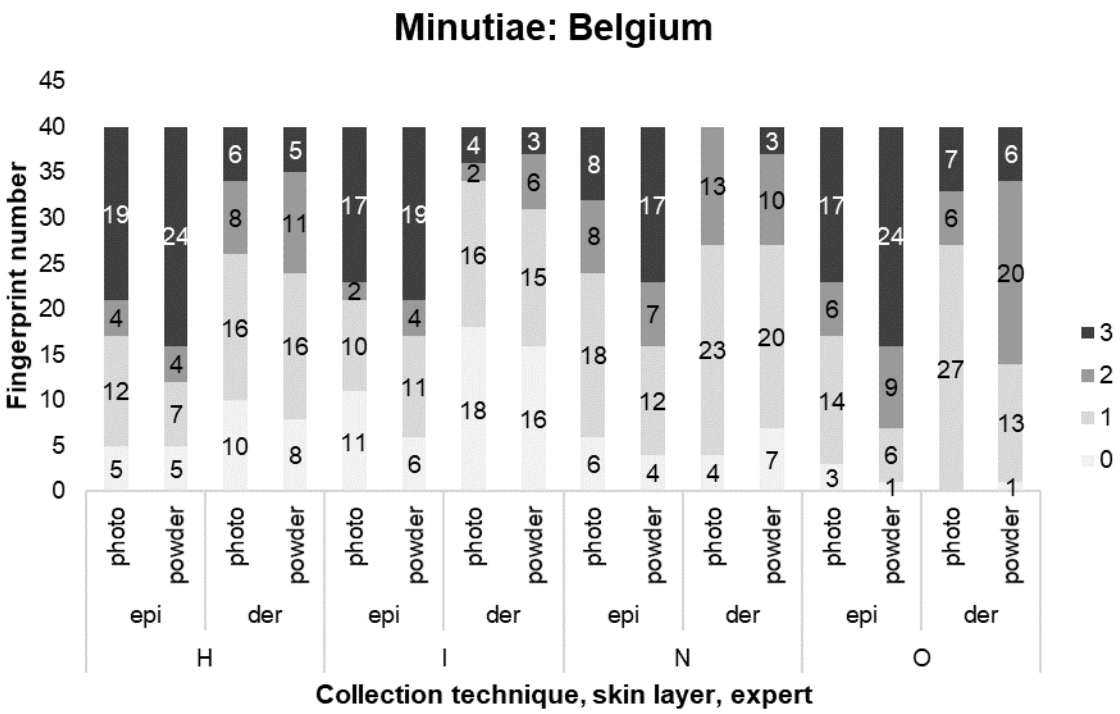

Figure 4.3.22 Number of fingerprints in minutiae number ranges as assessed by Belgian experts. Minutiae number ranges 0) 0 minutiae, 1) 1 – 7 minutiae, 2) 8 – 11 minutiae, 3) ≥ 12 minutiae. epi = epidermal, der = dermal.

Table 4.3.12 Percentages of fingerprints in minutiae number ranges as assessed by Belgian experts.

Skin layer	Minutiae ranges	Photo				Powder			
		H	I	N	O	H	I	N	O
Epidermal	≥ 12	47.5	42.5	20.0	42.5	60.0	47.5	42.5	60.0
	11 – 8	10.0	5.0	20.0	15.0	10.0	10.0	17.5	22.5
	7 – 1	30.0	25.0	45.0	35.0	17.5	27.5	30.0	15.0
	0	12.5	27.5	15.0	7.5	12.5	15.0	10.0	2.5
	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Dermal	≥ 12	15.0	10.0	0.0	17.5	12.5	7.5	7.5	15.0
	11 – 8	20.0	5.0	32.5	15.0	27.5	15.0	25.0	50.0
	7 – 1	40.0	40.0	57.5	67.5	40.0	37.5	50.0	32.5
	0	25.0	45.0	10.0	0.0	20.0	40.0	17.5	2.5
	Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Figure 4.3.23 and Table 4.3.13 show respectively the numbers and percentages of epidermal and dermal fingerprints collected using post-powder photography and powder categorised by the number of minutiae observed by trained fingerprint examiners from the UK, Sweden, and New Zealand. The experts from UK, Sweden, and New Zealand identified more than 20 minutiae on average in 53.9% of epidermal and 8.8% of dermal fingerprints collected using powder. The same number range of minutiae was identified by the same experts on average in 38.5% of epidermal and 3.7% of dermal fingerprints collected using post-powder photography. The experts from the UK, Sweden, and New Zealand identified between 20 and 10 minutiae on average in 14.8% of epidermal and 25.1% of dermal fingerprints collected using powder. The same number range of minutiae was identified by the same experts on average in 20% of epidermal and 25% of dermal fingerprints collected using post-powder photography. The experts from the UK, Sweden, and New Zealand identified between 9 and 1 minutiae on average in 28.2% of epidermal and 61% of dermal fingerprints collected using powder. The same number range of minutiae was identified by the same experts on average in 30.6% of epidermal and 52.5% of dermal fingerprints collected using post-powder photography. The experts from the UK, Sweden, and New Zealand identified no minutiae on average in 3.1% of epidermal and 5.1% of dermal fingerprints collected using powder. No minutiae were identified by the same experts on average in 10.9% of epidermal and 18.8% of dermal fingerprints collected using post-powder photography.

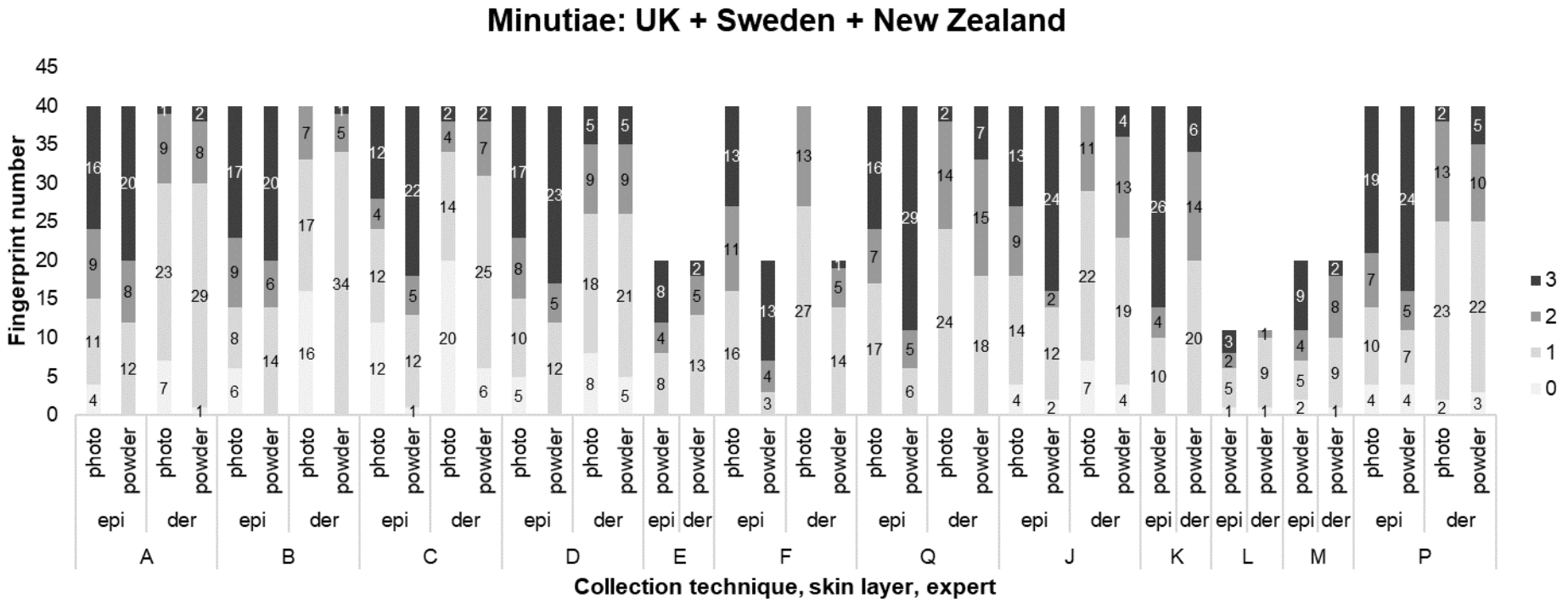

Figure 4.3.23 Number of fingerprints in minutiae number ranges as assessed by trained fingerprint examiners from the UK (A, B, C, D, E, F, Q), Sweden (J, K, L, M), and New Zealand (P). Minutiae number ranges 0) 0 minutiae, 1) 1 – 9 minutiae, 2) 10 – 20 minutiae, 3) > 20 minutiae. epi = epidermal, der = dermal.

Table 4.3.13 Percentages of fingerprints in minutiae number ranges as assessed by UK (A, B, C, D, E, F, Q), Swedish (J, K, L, M), and New Zealand (P) experts.

Skin layer	Minutiae ranges	Photo								Powder											
		A	B	C	D	F	Q	P	J	A	B	C	D	E	F	Q	J	K	L	M	P
Epidermal	> 20	40.0	42.5	30.0	42.5	32.5	40.0	47.5	32.5	50.0	50.0	55.0	57.5	40.0	65.0	72.5	60.0	65.0	27.3	45.0	60.0
	20 – 10	22.5	22.5	10.0	20.0	27.5	17.5	17.5	22.5	20.0	15.0	12.5	12.5	20.0	20.0	12.5	5.0	10.0	18.2	20.0	12.5
	9 – 1	27.5	20.0	30.0	25.0	40.0	42.5	25.0	35.0	30.0	35.0	30.0	30.0	40.0	15.0	15.0	30.0	25.0	45.4	25.0	17.5
	0	10.0	15.0	30.0	12.5	0.0	0.0	10.0	10.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	5.0	0.0	9.1	10.0	10.0
	Total (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Dermal	> 20	2.5	0.0	5.0	12.5	0.0	5.0	5.0	0.0	5.0	2.5	5.0	12.5	10.0	5.0	17.5	10.0	15.0	0.0	10.0	12.5
	20 – 10	22.5	17.5	10.0	22.5	32.5	35.0	32.5	27.5	20.0	12.5	17.5	22.5	25.0	25.0	37.5	32.5	35.0	9.1	40.0	25.0
	9 – 1	57.5	42.5	35.0	45.0	67.5	60.0	57.5	55.0	72.5	85.0	62.5	52.5	65.0	70.0	45.0	47.5	50.0	81.8	45.0	55.0
	0	17.5	40.0	50.0	20.0	0.0	0.0	5.0	17.5	2.5	0.0	15.0	12.5	0.0	0.0	0.0	10.0	0.0	9.1	5.0	7.5
	Total (%)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table 4.3.14, Figure 4.3.24, and Figure 4.3.25 show the resulting Krippendorff alpha reliability coefficients and their bootstrapped means and 95% confidence intervals for the fingerprint minutiae assessment performed by fingerprints examiners. Only data from examiners who analysed the full fingerprint dataset were included in calculations.

Table 4.3.14 Krippendorff alpha coefficients (α) for minutiae level assessment. Values** considered reliable (α ≥ 0.8). Values* with 95% confidence interval containing α ≥ 0.8. Only the experts who completed analysis of the full dataset were included.[8]

Country (number of experts)	Epidermal (n = 80)	Dermal (n = 80)	Powder (n = 80)	Photo (n = 80)
BE (n = 4)	0.759*	0.484	0.712	0.654
UK (n = 5)	0.761*	0.486	0.777*	0.632
UK (n = 4)	0.775*	0.508	0.827**	0.629
UK + SWE + NZ (n = 7)	0.801**	0.539	0.801**	0.456
UK + SWE + NZ (n = 6)	0.815**	0.548	0.827**	0.469

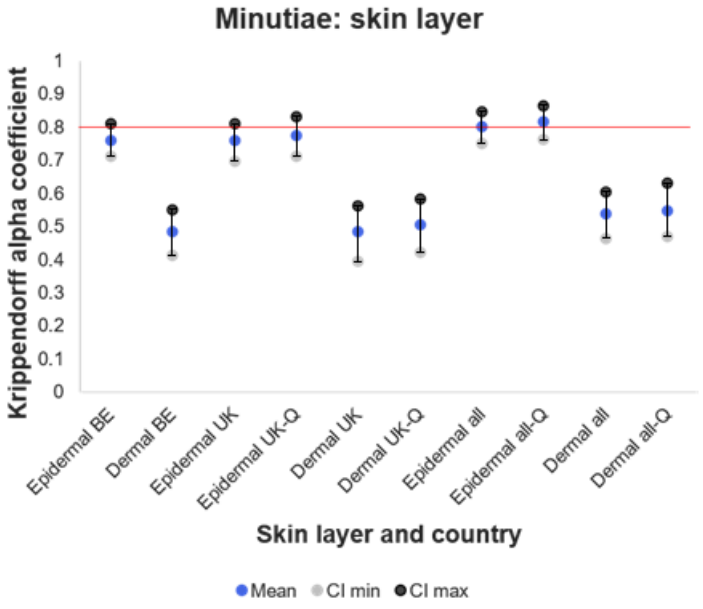

Figure 4.3.24 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for minutiae levels of epidermal and dermal fingerprints performed by fingerprint examiners. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[9]

[8] 'UK (n = 4)' represents the UK experts without the expert Q. 'UK + BE + SWE + NZ (n = 10)' represents the experts without the expert Q.

[9] 'all' in this case indicates experts who from UK + SWE + NZ analysed the full dataset. 'UK-Q' and 'all-Q' indicates coefficients for the same experts without the assessment of expert Q.

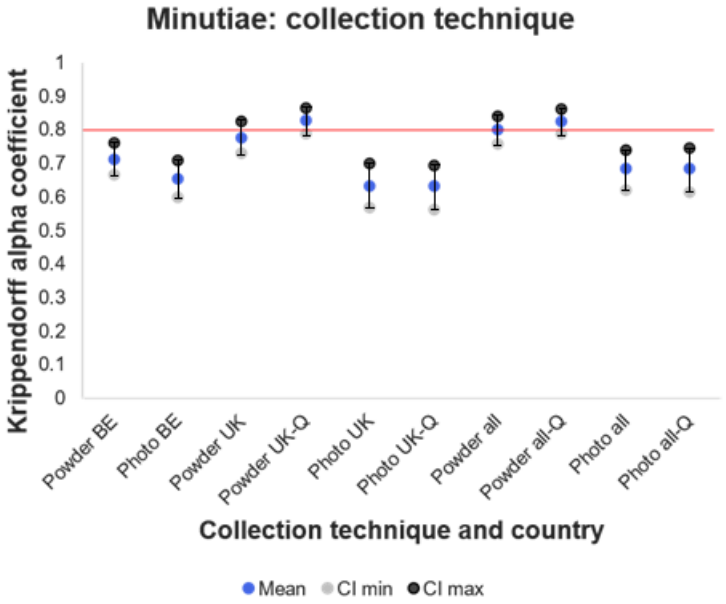

Figure 4.3.25 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for minutiae levels of fingerprints collected using post-powder photography and black powder performed by fingerprint examiners. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[10]

Sufficient agreement between the experts (α ≥ 0.8) was found in the cases of four UK examiners (UK examiners without the examiner Q) analysing fingerprints collected using powder (α = 0.827), all examiners pooled examining epidermal fingerprints (α = 0.801 for all experts, α = 0.815 for all minus Q expert) and fingerprints collected using powder (α = 0.801 for all experts, α = 0.827 for all minus Q expert) (Table 4.3.14). However, after calculating 95% confidence intervals of bootstrapped coefficient values, the reliability coefficient interval for minutiae of epidermal fingerprints assessed by the UK (with as well as without expert Q) and Belgian examiners and for minutiae of fingerprints collected using powder assessed by all UK experts contained α values equal to or greater than 0.8 (Figure 4.3.24, Figure 4.3.25), meaning sufficient inter-rater agreement when analysing minutiae assessment data within these four variables cannot be ruled out. Reliability coefficients from Table 4.3.14 are of higher values for minutiae assessment of epidermal fingerprints in comparison to dermal fingerprints and higher values of minutiae assessment in fingerprints collected using powder than in fingerprints collected using post-powder photography. Lack of overlap in 95%

[10] 'all' in this case indicates experts from UK + SWE + NZ analysed the full dataset. 'UK-Q' and 'all-Q' indicates coefficients for the same experts without the assessment of expert Q.

confidence interval ranges of epidermal and dermal fingerprints minutiae assessment performed by all categories of experts suggests there is a statistically supported difference between the inter-rater agreements when assessing the quality of epidermal and dermal fingerprints (Figure 4.3.24). Similar lack of overlap in 95% confidence interval ranges was observed for all groups of experts except Belgians when comparing minutiae assessment of powder and post-powder photography fingerprints, which suggests there is a statistically supported difference between the inter-rater agreements when assessing the minutiae of fingerprints collected using powder and post-powder photography in all groups of experts except Belgians (Figure 4.3.25).

For each of the experts from Belgium, the consistency score of quality categories and minutiae number ranges was calculated for each group of fingerprints divided according to the skin layer and collection technique. The consistency scores were calculated only for Belgian experts because the minutiae ranges reported by the experts from this country were based on the same minutiae number ranges the experts utilised in their fingerprint quality assessment as opposed to the experts from other countries who examined fingerprints in line with the holistic approach. Consistency scores equalled the number of individual fingerprints which were assigned the same quality category as minutiae number range within each skin layer and collection technique group (maximum of 40). The minutiae number ranges ‘0’ (0 minutiae detected) and ‘1’ (between 1 and 7 minutiae detected) were grouped into one to facilitate the comparison between the quality categories and minutiae number ranges. The resulting consistency scores are reported in Table 4.3.15. Expert H had the highest frequency of the maximum consistency score (40) for epidermal and dermal fingerprints collected using powder and epidermal fingerprints collected using post-powder photography. Expert H mis-classified the quality/minutiae number range for one fingerprint (2.5%) in the group of dermal fingerprints collected using post-powder photography. Similarly, expert I showed full consistency (40 out of 40 consistently classified fingerprints for both quality and minutiae ranges assessment) in cases of epidermal and dermal fingerprints collected using powder and misclassified one fingerprint (2.5%) from each of the groups of epidermal and dermal fingerprints collected using post-powder photography. Experts N and O assigned fingerprint quality and minutiae number ranges with more inconsistencies in comparison to the first two Belgian experts.

Expert N had the highest consistency score in case of epidermal fingerprints collected using powder (25% inconsistencies). The same expert misclassified the quality in relation to minutiae number ranges (or *vice versa*) in more than half of the fingerprints collected using post-powder photography (52.5% inconsistencies in epidermal fingerprints, 55% inconsistencies in dermal fingerprints). Expert O also had the highest consistency score in case of epidermal fingerprints collected using powder with two fingerprints that did not match their classification of quality and minutiae number ranges (5% inconsistencies). Expert O had the lowest consistency score in case of dermal fingerprints collected using post-powder photography (42.5% inconsistencies).

Table 4.3.15 Consistency score of minutiae number ranges and quality categories reported by Belgian experts. Consistency score is expressed as the number of individual fingerprints which had the same quality assessment and minutiae number range assessment within each skin layer and collection technique category (maximum consistency score value is 40). Minutiae number ranges 0 and 1 were grouped for calculations of the score.

Expert	Epidermal Photo	Epidermal Powder	Dermal Photo	Dermal Powder
H	40	40	39	40
I	39	40	39	40
N	19	30	18	23
O	30	38	23	33

4.3.2.3 Epidermal-dermal fingerprint comparison outcome

Fingerprint examiners were asked to assign a comparison outcome to each pair of epidermal and dermal fingerprints. Figure 4.3.26 and Figure 4.3.27 show the comparison outcomes for each epidermal-dermal fingerprint pair (collected using powder and photography) as assigned by all the experts who took part in the study. There were six cases of epidermal-dermal fingerprint pairs collected using powder in which fingerprint examiners all agreed on the exclusion outcome (fingerprint pairs number 16, 19, 23, 27, 35, 39 in Figure 4.3.26). Similarly, there were three cases of epidermal-dermal fingerprint pairs collected using photography in which fingerprint examiners all agreed on the exclusion outcome (pairs number 22, 23, and 34 in Figure 4.3.27). There were no powder or photography fingerprint pairs where the experts agreed on the identification

outcome but the pairs with numbers 20 and 24 collected using powder had all but one of the experts agreeing on the identification outcome (Figure 4.3.26). There were five cases of epidermal-dermal fingerprint pairs collected using powder in which the experts arrived at an inconclusive comparison outcome; the experts were finding the fingerprints as insufficient for comparison or were unable to exclude the individual from a theoretical pool of potential candidates for identification (pairs number 1, 2, 12, 32, 40 in Figure 4.3.26). There were nine cases of epidermal-dermal fingerprint pairs collected using photography in which the experts arrived at one of the inconclusive comparison outcomes (pairs number 1, 2, 4, 5, 8, 9, 11, 21, 32 in Figure 4.3.27). Remaining epidermal-dermal fingerprints pairs collected using both collection techniques had a mixture of opinions expressed by the fingerprint examiners regarding the identification outcome.

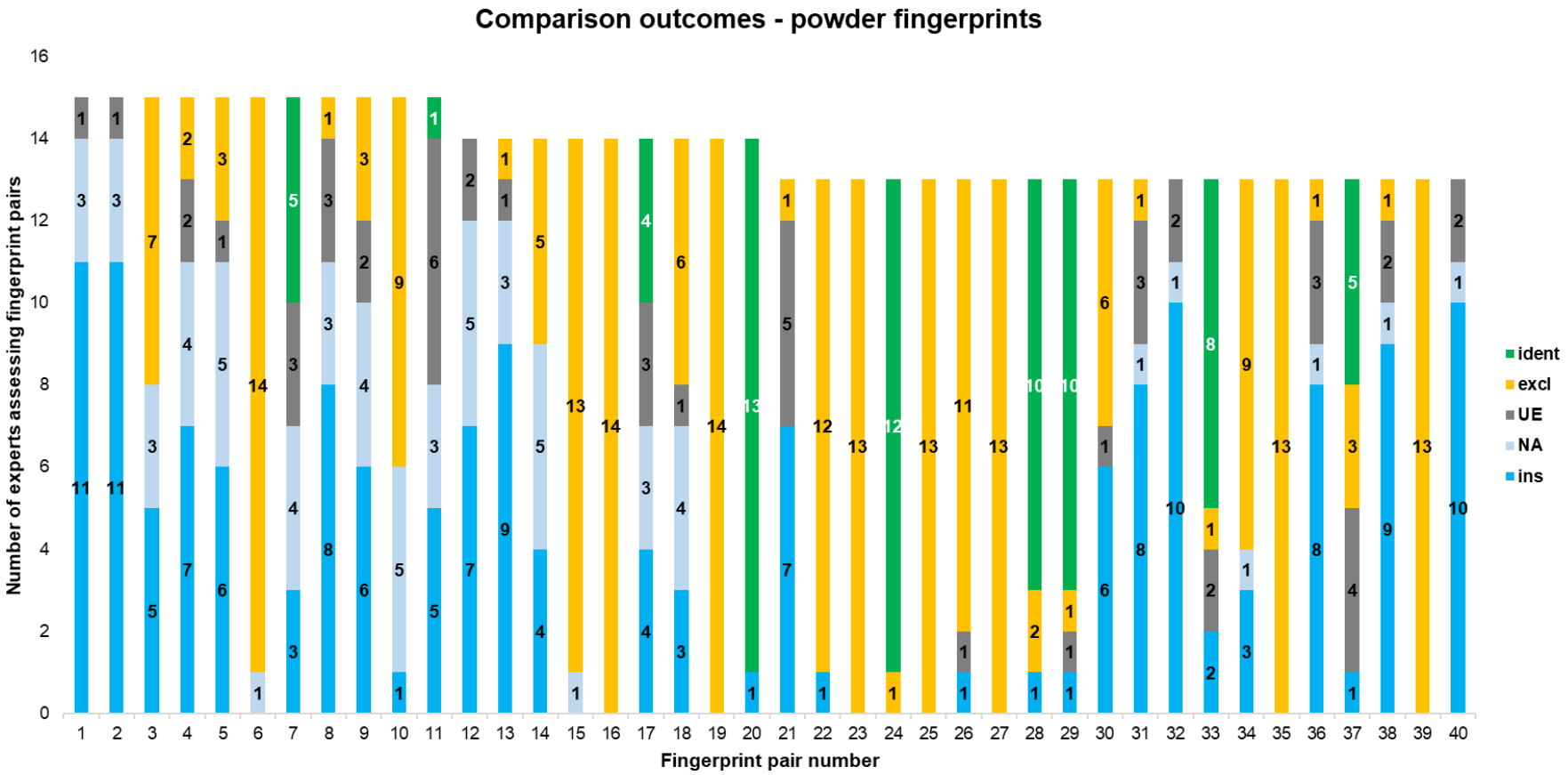

Figure 4.3.26 Comparison outcomes assigned by fingerprint examiners to each epidermal-dermal fingerprint pair collected using black powder. ‘ident’ = identification, ‘excl’ = exclusion, UE = unable to exclude, NA = not applicable (unable to compare), ‘ins’ = insufficient for comparison.

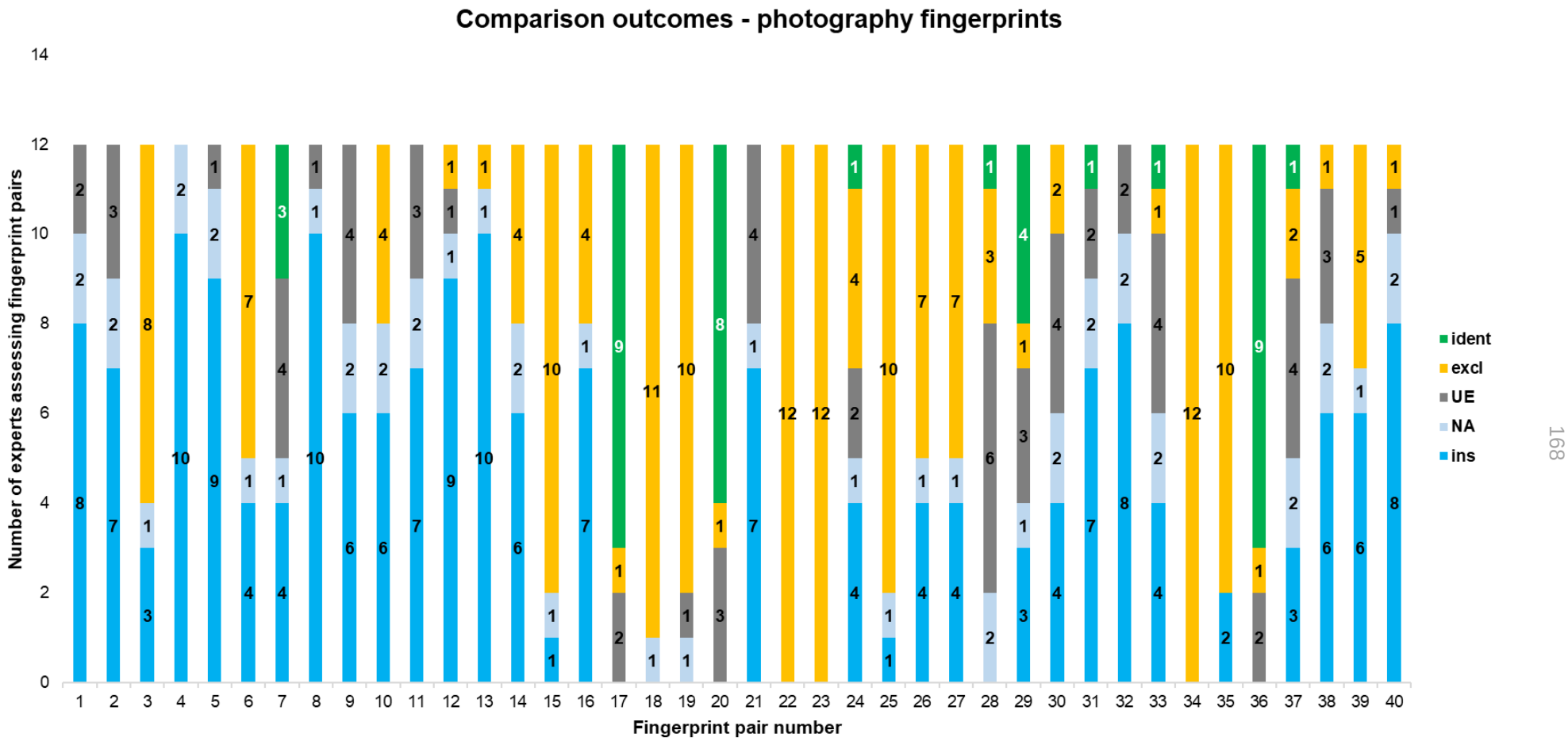

Figure 4.3.27 Comparison outcomes assigned by fingerprint examiners to each epidermal-dermal fingerprint pair collected using photography. ‘ident’ = identification, ‘excl’ = exclusion, UE = unable to exclude, NA = not applicable (unable to compare), ‘ins’ = insufficient for comparison.

Figure 4.3.28 shows the number of fingerprint comparisons performed by trained fingerprint examiners. The comparison outcomes are organised into outcomes that matched and did not match expected outcomes of matched (epidermal-dermal fingerprint pair which originates from the same digit) and unmatched (epidermal-dermal fingerprint pair which originates not from the same digit) epidermal-dermal fingerprint pairs. There was a higher number of correct exclusions observed than the number of correct identifications for all experts regardless of the fingerprint collection technique. Figure 4.3.28 also shows the numbers of false exclusions made by the experts when comparing epidermal and dermal fingerprints. Expert Q had the highest numbers of false exclusions - 8 and 9 for fingerprints collected using post-powder photography and powder respectively. There were no false identifications (false positives) observed in the dataset.

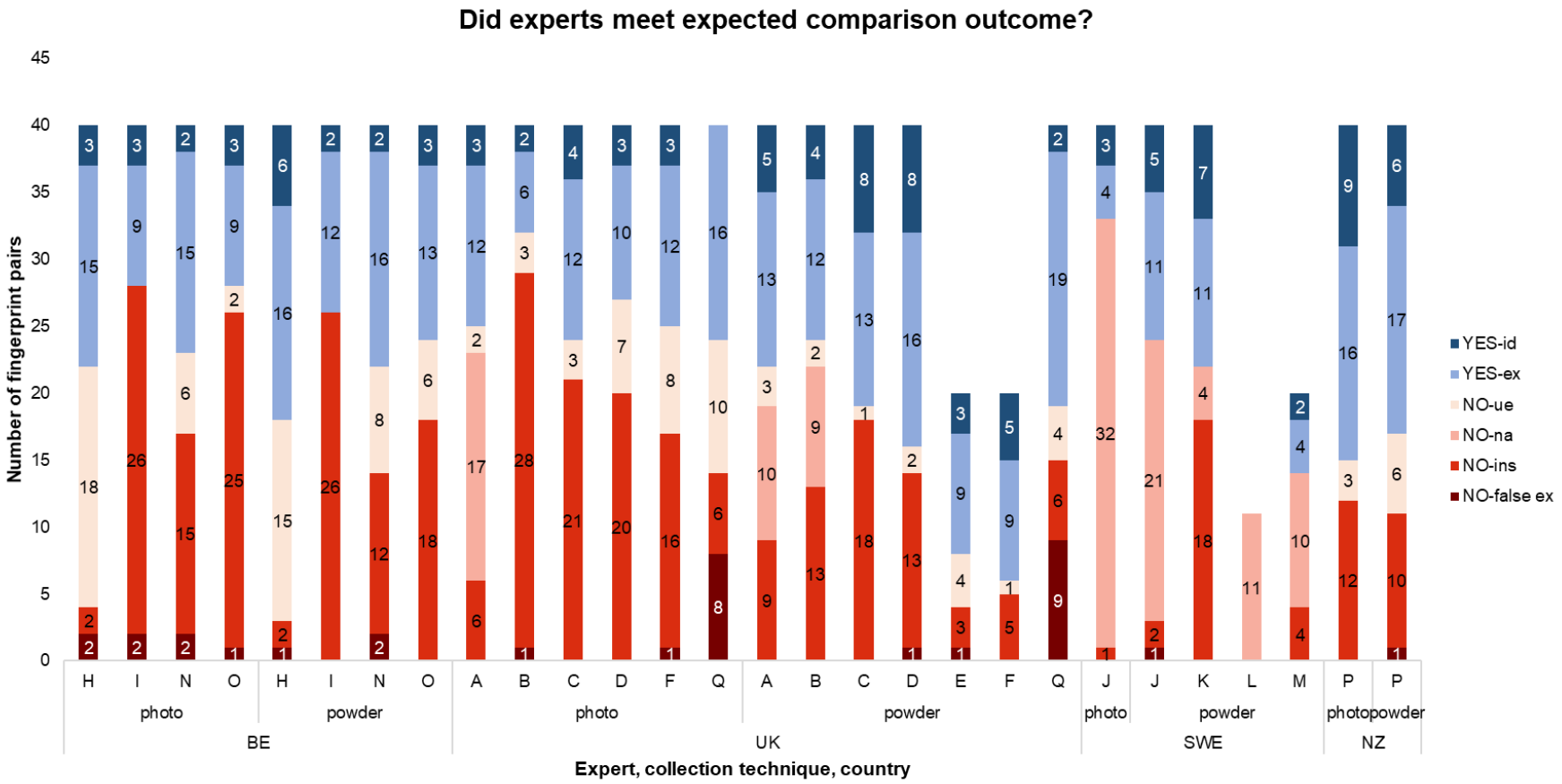

Figure 4.3.28 Summary of epidermal-dermal fingerprint pairs comparison outcome assessed by fingerprint examiners. YES-id – correctly identified. YES-ex – correctly excluded. NO-ue – unable to exclude, NO-na – not applicable, NO-ins – insufficient, NO-false ex – falsely excluded.

The percentages of epidermal-dermal fingerprint pairs that could not be identified or excluded by fingerprint examiners who completed the analysis of the full dataset within at least one of the fingerprint collection technique category (i.e. those classified as ‘insufficient’, ‘unable to exclude’, and ‘NA’) are included in Table 4.3.16. False exclusions are not included in the table. Belgian experts reached such inconclusive outcomes of fingerprint comparison on average in 54.4% of fingerprint pairs collected using powder and on average in 57.5% of fingerprint pairs collected using post-powder photography. UK experts reached inconclusive outcomes of fingerprint comparison on average in 40% of fingerprint pairs collected using powder and on average in 61.3% of fingerprint pairs collected using post-powder photography. Experts from Sweden could not identify or exclude on average 56.3% of fingerprint pairs collected using powder. One of the Swedish experts who also completed the analysis of fingerprints collected using post-powder photography could not identify or exclude 82.5% of fingerprint pairs collected using post-powder photography. The expert from New Zealand was the only expert who reached one of the inconclusive comparison outcomes in fewer fingerprint pairs collected using post-powder photography (37.5%) than in fingerprint pairs collected using powder (40%).

Table 4.3.16 Percentages of epidermal-dermal fingerprint pairs that were classified by the fingerprint examiners as ‘insufficient’, ‘unable to exclude’, and ‘NA’.

	Powder					**Photo**					
BE experts	**H**	**I**	**N**	**O**		**H**	**I**	**N**	**O**		
%	42.5	65.0	50.0	60.0		50.0	65.0	52.5	67.5		
UK experts	**A**	**B**	**C**	**D**	**Q**	**A**	**B**	**C**	**D**	**F**	**Q**
%	55.0	60.0	47.5	37.5	35.0	62.5	77.5	60.0	67.5	60.0	40.0
SWE experts	**J**	**K**				**J**					
%	57.5	55.0				82.5					
NZ expert	**P**					**P**					
%	40.0					37.5					

The accuracy per class was calculated as a sum of experts’ correct identifications, correct exclusions, and inconclusive outcomes, which were assigned to fingerprint pairs by all of the experts analysing them, divided by the

total number of fingerprint pairs in each collection technique category. The accuracy percentages for each expert who completed at least one full dataset within the fingerprint collection technique category are included in Table 4.3.17. The accuracy percentage for correct fingerprint comparison outcome assessed by Belgian experts was on average 56.3% for fingerprint pairs collected using powder and on average 59.4% in case of fingerprint pairs collected using post-powder photography. The accuracy percentage for UK experts was on average 62.5% of fingerprint pairs collected using powder and 57.1% for fingerprint pairs collected using post-powder photography. Experts from Sweden achieved average accuracy percentage of 55% for fingerprint pairs collected using powder. One of the Swedish experts who also completed the analysis of fingerprints collected using post-powder photography had the accuracy percentage of 40% for fingerprint pairs collected using post-powder photography. The expert from New Zealand, similarly as Belgian experts, achieved higher accuracy percentage for comparison of fingerprint pairs collected using post-powder photography (85%) than for comparison of fingerprint pairs collected using powder (70%).

Table 4.3.17 Accuracy percentages calculated for experts' epidermal-dermal fingerprint comparison for each fingerprint collection technique. NA – data not available for calculation.

Country	Expert	Accuracy photo (%)	Accuracy powder (%)
Belgium	H	67.5	67.5
	I	52.5	47.5
	N	65.0	57.5
	O	52.5	52.5
UK	A	60.0	57.5
	B	42.5	52.5
	C	62.5	65.0
	D	55.0	72.5
	E	NA	NA
	F	60.0	NA
	Q	62.5	65.0
Sweden	J	40.0	52.5
	K	NA	57.5
	L	NA	NA
	M	NA	NA
New Zealand	P	85.0	70.0

Table 4.3.18 presents the numbers of epidermal-dermal fingerprints pairs in which at least one fingerprint was deemed unusable and the experts were still able to compare the fingerprints and arrive at an identification or exclusion outcome. Only data from the experts who completed the analysis of the full dataset were included in the table. The numbers were higher for exclusion outcomes than for identification outcomes. Three identification outcomes with at least one fingerprint deemed as unusable were recorded by expert C (two identification outcomes for fingerprint pairs collected using post-powder photography and one for fingerprint pair collected using powder). One identification outcome with at least one fingerprint deemed unusable was recorded by expert B for fingerprint pair collected using powder. The expert with the highest number of exclusion outcomes with at least one fingerprint deemed unusable was expert H (14 exclusions for fingerprint pairs collected using post-powder photography, 11 exclusions for fingerprint pairs collected using powder). Two out of the 14 exclusions for post-powder photography and one out of the 11 exclusions for powder made by the expert H were false exclusions. The expert with no identification and exclusion outcomes with at least one fingerprint deemed unusable was expert J.

Table 4.3.18 Numbers of epidermal-dermal fingerprint pairs in which at least one fingerprint was deemed unusable for comparison and the expert was able to reach identification or exclusion outcome. Only the experts who analysed the full dataset were included.

Country	Expert	Photo		Powder	
		ID	Excl. (False)	ID	Excl. (False)
BE	H	0	14 (2)	0	11 (1)
BE	I	0	9 (1)	0	7
BE	N	0	5	0	8
BE	O	0	3	0	0
UK	A	0	6	0	7
UK	B	0	2	1	8
UK	C	2	10	1	4
UK	D	0	6	0	5
UK	Q	0	3	0	2
SWE	J	0	0	0	0
NZ	P	0	4	0	5 (1)

Table 4.3.19 and Figure 4.3.29 show the resulting Krippendorff alpha reliability coefficients and their bootstrapped means and 95% confidence intervals for epidermal-dermal fingerprint comparison performed by fingerprints examiners classifying outcomes into five categories. Only data from the experts who completed the analysis of the full dataset were included in the analysis. In all expert groups, no sufficient agreement between the experts ($\alpha \geq 0.8$) was found (Table 4.3.19). Confidence intervals (95%) of bootstrapped coefficient values were calculated and none of the resulting reliability coefficient intervals for epidermal-dermal fingerprint comparison (with five outcome categories) had α values equal to or greater than 0.8 (Figure 4.3.29), meaning there was no sufficient inter-rater agreement found when performing epidermal-dermal fingerprint comparison with five outcome categories. Reliability coefficients from Table 4.3.19 are of higher values for comparison outcomes of fingerprints collected using powder in comparison to fingerprints collected using post-powder photography. However, there are only two groups of experts, all experts pooled and pooled experts without the expert Q, which lack overlap in 95% confidence

interval ranges for fingerprints collected using powder and post-powder photography (Figure 4.3.29). The lack of overlap in the 95% confidence intervals suggests there is a statistically supported difference between the inter-rater agreements only in these two groups of experts when comparing epidermal-dermal fingerprints collected using powder and post-powder photography with five comparison outcomes categories (Figure 4.3.29).

Table 4.3.19 Krippendorff alpha coefficients (α) for identification outcome assessment in five categories (identification, exclusion, unable to exclude, not applicable, insufficient).[11]

Country (number of experts)	Pooled collection techniques (n = 80)	Powder (n = 40)	Photo (n = 40)
BE (n = 4)	0.318	0.360	0.274
UK (n = 5)	0.400	0.472	0.315
UK (n = 4)	0.514	0.585	0.427
UK+ BE + SWE + NZ (n = 11)	0.338	0.399	0.271
UK+ BE + SWE + NZ (n = 10)	0.358	0.425	0.285

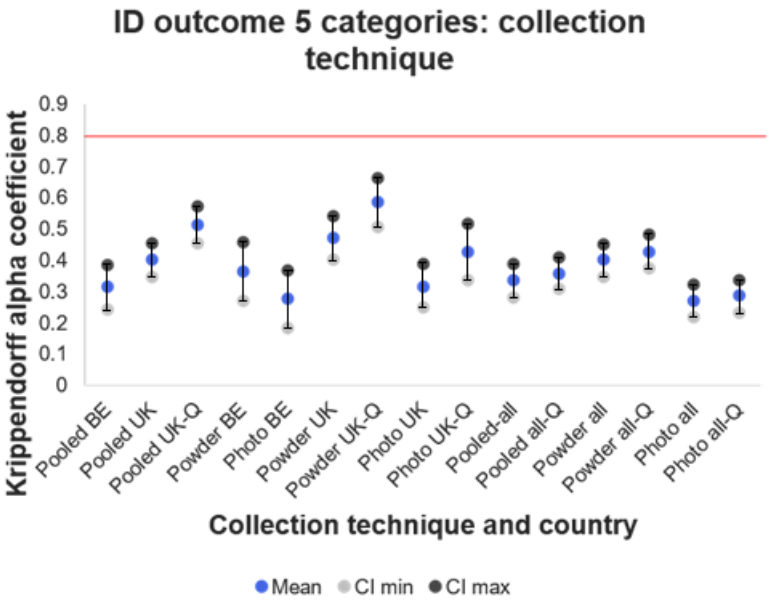

Figure 4.3.29 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for identification outcome assessment into five categories performed by fingerprint examiners. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[12]

[11] 'UK (n = 4)' represents the UK experts who analysed the full dataset without the expert Q. 'UK + BE + SWE + NZ (n = 10)' represents the experts who analysed the full dataset without the expert Q.
[12] 'UK-Q' and 'all-Q' indicates respectively coefficients for experts of UK and UK + BE + SWE + NZ who analysed the full dataset without the assessment of expert Q.

Table 4.3.20 and Figure 4.3.30 show the resulting Krippendorff alpha reliability coefficients and their bootstrapped means and 95% confidence intervals for epidermal-dermal fingerprint comparison performed by fingerprints examiners classifying outcomes into three categories. Only data from the experts who completed the analysis of the full dataset were included in the analysis. In all expert groups, no sufficient agreement between the experts ($\alpha \geq 0.8$) was found (Table 4.3.20). However, confidence intervals (95%) of bootstrapped coefficient values were calculated and three of the resulting reliability coefficient intervals for epidermal-dermal fingerprint comparison (with three outcome categories) included values equal to or greater than 0.8 (Figure 4.3.30), meaning there was sufficient inter-rater agreement found between four UK experts (without the expert Q) when performing epidermal-dermal fingerprint comparison with three outcome categories regardless of fingerprint collection technique. Reliability coefficients from Table 4.3.19 are of higher values for comparison outcomes of fingerprints collected using powder in comparison to fingerprints collected using post-powder photography in all groups but four UK experts (without the expert Q). However, only the Belgian experts lack an overlap in 95% confidence interval ranges for fingerprints collected using powder and post-powder photography (Figure 4.3.30). The lack of overlap in the 95% confidence intervals suggests there is a statistically supported difference between the inter-rater agreements only for Belgian experts when comparing epidermal-dermal fingerprints collected using powder and post-powder photography with three comparison outcomes categories (Figure 4.3.30).

Table 4.3.20 Krippendorff alpha coefficients (α) for identification outcome assessment in three categories (identification, exclusion, unable to reach conclusion). Values* with 95% confidence interval containing α ≥ 0.8.[13]

Country (number of experts)	Pooled collection techniques (n = 80)	Powder (n = 40)	Photo (n = 40)
BE (n = 4)	0.546	0.664	0.422
UK (n = 5)	0.581	0.576	0.571
UK (n = 4)	0.734*	0.726*	0.732*
UK+ BE + SWE + NZ (n = 11)	0.548	0.613	0.468
UK+ BE + SWE + NZ (n = 10)	0.588	0.670	0.489

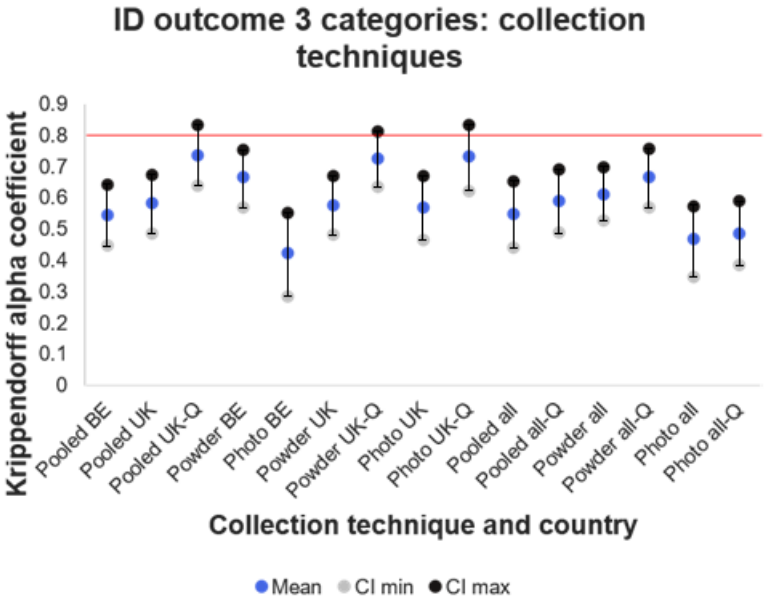

Figure 4.3.30 Bootstrapped (1000 iterations) mean Krippendorff alpha coefficients (α) with 95% confidence intervals for identification outcome assessment into three categories performed by fingerprint examiners. Red line denotes a minimal threshold for data reliability, values α ≥ 0.8 are considered reliable.[14]

Figure 4.3.31 shows a plot between the number of correct identifications and exclusions made by nine fingerprint examiners and their self-reported years of experience for fingerprint pairs collected using powder. The number of experts

[13] 'UK (n = 4)' represents the UK experts who analysed the full dataset without the expert Q. 'UK + BE + SWE + NZ (n = 10)' represents the experts who analysed the full dataset without the expert Q.
[14] 'UK-Q' and 'all-Q' indicates respectively coefficients for experts of UK and UK + BE + SWE + NZ who analysed the full dataset without the assessment of expert Q.

was insufficient to perform a reliable statistical analysis and draw conclusions regarding the years of experience and expert's performance in epidermal-dermal fingerprint analysis.

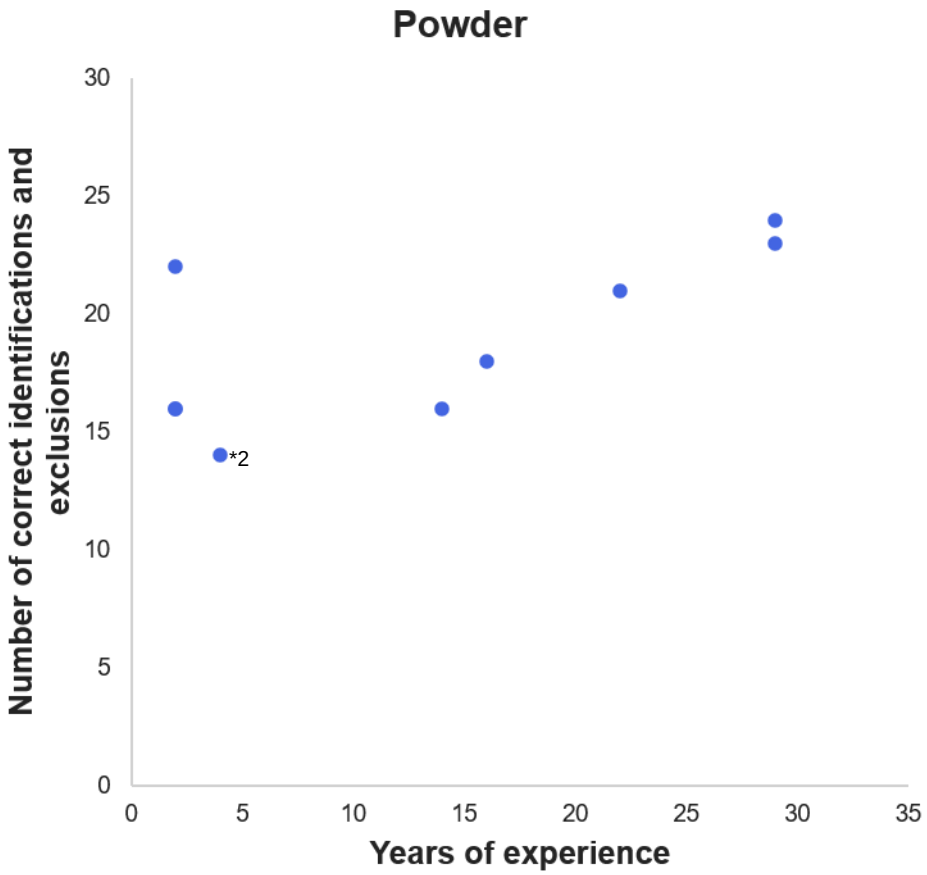

Figure 4.3.31 The numbers of correct identifications and exclusions in epidermal-dermal fingerprint pairs collected using powder plotted against years of experience for nine experts who supplied the information. Only the experts who analysed the full dataset were included. *2 = two overlapping data points.

Figure 4.3.32 shows a plot between the number of correct identifications and exclusions made by nine fingerprint examiners and their self-reported years of experience for fingerprint pairs collected using post-powder photography. The number of experts was insufficient to perform a reliable statistical analysis and draw conclusions regarding the years of experience and expert's performance in epidermal-dermal fingerprint analysis.

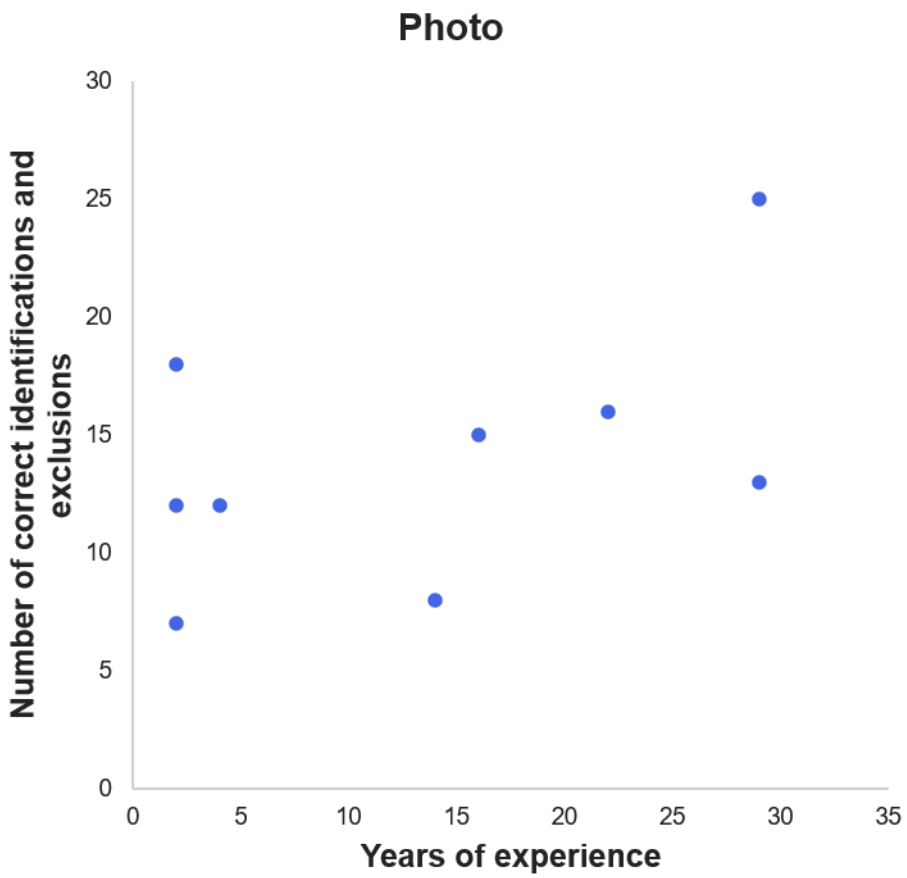

Figure 4.3.32 The numbers of correct identifications and exclusions in epidermal-dermal fingerprint pairs collected using post-powder photography plotted against years of experience for nine experts who supplied the information. Only the experts who analysed the full dataset were included.

4.4 Discussion

4.4.1 Intra- and inter-observer agreement in epidermal-dermal fingerprint quality and usability agreement

Intra-observer variation in the author's (baseline) assessment of epidermal and dermal fingerprint quality and usability was calculated using Krippendorff alpha coefficient and its 95% confidence interval. The baseline quality of fingerprints was assessed in three categories – 'unsuitable for comparison', 'suitable for manual comparison', and 'suitable for comparison using IDENT1 system'. When fingerprint quality assessment was translated into fingerprint usability (for both baseline and expert assessment), one of two values was given to each assessed fingerprint – whether it was sufficient for further comparison or insufficient for further comparison. It is important to note that what is defined as quality and usability in the present study, could be fused into one term and defined as fingerprint sufficiency and/or fingerprint value, and this approach can be found across the published literature (Neumann *et al.*, 2013; Ulery *et al.*, 2013, 2014).

The results of baseline fingerprint quality assessment suggest that what is considered to be good intra-observer agreement could not be statistically ruled out for prints taken using all collection techniques, based on Krippendorff alpha coefficient confidence interval calculations (Krippendorff, 2013). Similar values of Krippendorff alpha coefficient and their confidence intervals were calculated for baseline fingerprint usability intra-observer agreement. Although the usability intra-observer agreement values were lower than intra-observer agreement in the assessment of quality, they were not statistically different due to their overlapping 95% confidence intervals, which was to be expected due to the fact that the variables are inter-connected and one stems from the other. Therefore, when discussed within the context of other published research outputs, both intra-observer agreement in baseline quality and usability assessment will be discussed at the same time.

Both variables, fingerprint quality and usability, are a part of the analysis step of the ACE-V fingerprint examination process. The sources dealing with intra-observer variation during the analysis phase of fingerprint examination where fingerprint quality/sufficiency is assessed, are still scarce and not directly

comparable with the results of present intra-observer agreement during fingerprint quality and usability assessment. The past research focused mainly on studying intra-observer variation of the comparative and evaluative phases of fingerprint examination. The baseline fingerprint quality and usability assessment agreement results are not directly comparable with the study performed by Ulery *et al.* (2012) either due to their different approach in intra-examiner agreement monitoring, however, they found greater inconsistency in experts' assessment of fingerprint sufficiency in cases where the fingerprints were deemed of lesser quality. Since the quality of epidermal and dermal fingerprints collected from elderly individuals is generally considered to be low (Chacko and Vaidya, 1968; Okajima, 1979), the expectations for high intra-observer agreement in the quality assessment are reduced. Although the studies performed by Dror *et al.* (2011) and Swofford *et al.* (2013) deal with intra-examiner variation during the analysis phase of fingerprints, both of these studies show intra-examiner inconsistencies in minutiae counts in fingerprints of varying quality. However, neither of the two aforementioned studies would be directly comparable to the current results of intra-observer variation in fingerprint quality and usability assessment, as according to Hicklin *et al.* (2011) the scientists should distinguish between intra-observer variation of quantity of observed identifying features from intra-observer variation in quality/clarity assessment of the fingerprint. At the same time, it could be argued that the number of minutiae and fingerprint quality are closely interconnected, as Neumann *et al.* (2013) state that the most decisive factors when assessing fingerprint sufficiency are: number of minutiae, certainty associated with type and location of minutiae, and specificity of a spatial relationship between minutiae.

The difference in intra-observer agreement in baseline fingerprint quality and usability assessment conducted by the author could be explained by a lack of formal fingerprint examination training combined with a lack of specific detailed instructions/criteria in the methods utilised to distinguish between fingerprints sufficient and insufficient for further comparison (Neumann *et al.*, 2013). Furthermore, the changes in the quality and usability assessment could be caused by outside influence such as increased viewings of fingerprints of challenging quality and increased amount of background reading about the ACE-V process as suggested in the literature (Dror *et al.*, 2011; Ulery *et al.*, 2012;

Fraser-MacKenzie *et al.*, 2013). In the time between the first and the second baseline quality and usability assessment, the author spent substantial time talking to and observing multiple fingerprint examiners whilst they were performing the analysis and comparisons of epidermal-dermal fingerprint sets which arguably affected the authors' perception of ‘good’ and ‘bad’ fingerprints. The change between the initial and second baseline fingerprint quality assessment could also be influenced by the fact that the author had increased the number of observed and analysed fingerprints which could be compared. Similar changes in observer consistency have been observed when viewing radiographic images, with an increase in experience spent analysing them leading to an increase in repeatability scores (Reed *et al.*, 2010). However, it is important to stress that radiographic images are not fingerprints.

The inter-observer variation in the experts’ assessment of epidermal and dermal fingerprint quality and usability was also calculated using Krippendorff alpha coefficient and its 95% confidence interval. The experts assessed the quality and usability of a subsample of fingerprints which were organised for statistical comparison purposes either by the skin layer (epidermal and dermal fingerprints) or collection technique (fingerprints collected using powder and post-powder photography). When experts’ agreement was compared for fingerprints organised according to the skin layer, the collection techniques were pooled for both epidermal and dermal fingerprint groups. Similarly, when experts’ agreement was compared for fingerprints organised according to the collection technique, the skin layers were pooled for fingerprints collected using powder and fingerprints collected using post-powder photography.

The performance in the baseline fingerprint quality assessment of the author was compared to the fingerprint quality assessment of the UK experts also using Krippendorff alpha coefficient and its 95% confidence interval. Only the analyses of the UK experts were taken into consideration, as they were the experts who were using the same quality criteria employed by their agency as the quality criteria utilised by the author. The inter-observer agreement between the author and the UK fingerprint examiners were calculated only for fingerprint quality and not usability assessment. Good levels of agreement, as defined by Krippendorff (2013), could not be statistically excluded between the baseline quality

assessment and three of the UK experts when comparing the group of epidermal fingerprints (pooled collection techniques) and the group of powder fingerprints (pooled skin layers). The fact that there was even a possibility for good agreement between an individual with no training in fingerprint assessment and experienced fingerprint examiners agrees with the findings of Neumann *et al.* (2013) who suggest that factors such as years of experience and expert status do not seem to play a role in establishing fingerprint sufficiency. The study of Schiffer and Champod (2007) argues that whilst the level of training does play a role during the analysis part of fingerprint assessment, it is important to note that they were studying the numbers of minutiae annotated by trained and untrained students which makes this study more relevant for comparison with section 4.4.3.

The inter-expert agreement when assessing the quality of fingerprints was assessed only for experts from the UK and Belgium as these were the only countries with a sufficient number of experts to perform the inter-examiner data analysis. For the dermal fingerprints, neither of the two groups of the experts met the requirements for statistically sufficient agreement in the quality assessment. Similarly, for the fingerprints collected using photography, neither of the two groups of experts met the requirements for statistically sufficient agreement in the quality assessment. These findings suggest that there could be more complex and/or lower quality fingerprints among dermal fingerprints and fingerprints collected using photography as argued by Ulery *et al.* (2012). The low inter-examiner agreement in fingerprint quality assessment was documented in numerous studies (Evett and Williams, 1996; Langenburg, 2009; Ulery *et al.*, 2012). Furthermore, Neumann *et al.* (2013) found large inter-examiner variability in reported quality judgements and attribute it to the lack of consistency in definition and understanding of the quality assessment concepts within the fingerprint community. The study of Hicklin *et al.* (2011) showed that during their analysis of fingerprints the experts agreed on identifying relevant areas of interest in fingerprints but assigned different degrees of confidence to the features in the areas which again show that inter-examiner variability in quality assessment of fingerprints is an ongoing issue. To improve the inter-examiner agreement and combat subjectivity in fingerprint quality assessment, Hicklin *et al.* (2013) suggest that their automatic algorithm will aid with ensuring consistency in the assessment of fingerprint quality. The authors recommend the use of the automated clarity

maps especially in the cases of fingerprints which are challenging to analyse (such as dermal fingerprints and or epidermal fingerprints collected from elderly individuals) allowing them to be flagged for additional quality assurance review. Despite the abovementioned studies, what Krippendorff (2013) considers as good agreement coefficients in the quality assessment were found between the UK experts assessing epidermal fingerprints and the fingerprints collected using powder, and between the Belgian experts assessing the quality of epidermal fingerprints. The levels of agreement observed in those cases could suggest that the experts adhere to the same protocol despite their subjectivity as suggested by Neumann *et al.* (2013). The presence of these agreement levels could also be explained by the fact that the fingerprint examiners involved in the study are coming in contact more with epidermal fingerprints collected using powder rather than dermal fingerprints or fingerprints collected using photography. Similarly, the difference in expert agreement in quality assessment between the two fingerprint collection techniques in the case of the UK experts shows that the experts exhibited better consistency in quality assessment in the case of powder fingerprints that are more commonly encountered in their practice than fingerprints collected using photography (personal communication, B. Robertson 2018). The higher frequency of fingerprints collected using powder could be explained by the fact that powder is still one of the most common fingerprint collection techniques employed on deceased individuals due to its cost-effectiveness and ease of manipulation (Principe and Verbeke, 1973; Morgan *et al.*, 2018). It is important to stress that in both cases where the UK experts had a good level of agreement it was a group of experts without expert Q. Since expert Q did not have access to a fingerprint comparator and only used a magnifying glass for his assessment of fingerprints, this technical difference could affect the effectivity and accuracy of his/her quality assessment causing his/her quality analysis to be more variable to the rest of the UK experts.

The inter-expert agreement when assessing the usability of fingerprints was assessed separately for experts from the UK and Belgium, and then for all experts who analysed the full dataset pooled together. A good level of agreement in fingerprint usability assessment was found for UK experts (without expert Q) in case of epidermal fingerprints and fingerprints collected using powder, and for all experts pooled together in case of epidermal fingerprints. However, there was no

statistically supported difference found between expert usability agreements when assessing agreement coefficient confidence intervals between epidermal and dermal, and between fingerprints collected using powder and photography. The low consistencies in the inter-expert assessment of fingerprint usability (sufficiency) were also encountered by other research groups (Ulery *et al.*, 2011, 2012, 2013; Neumann *et al.*, 2013; Eldridge *et al.*, 2020). The inconsistencies, similarly to fingerprint quality may be affected by multiple factors such as lack of consistency in terminology and understanding of the concepts, and/or fluidity of the term 'fingerprint value' – the value is described as a continuum rather than binary determinant (Neumann *et al.*, 2013; Ulery *et al.*, 2013). Moreover, the overall low quality of fingerprints studied by the expert for the purposes of this thesis could have an effect on the low inter-observer agreement in fingerprint usability assessment (Eldridge *et al.*, 2020). In their study, Eldridge *et al.* (2020) claim that fingerprint examiners are able to reach unanimity assigning the value to high-quality fingerprints while unable to reach unanimity when assigning no value to low-quality fingerprints.

It is up for discussion whether different terminology should be used in any potential future research concerning fingerprint quality/usability/sufficiency/value assessment agreement between fingerprint examiners. Fingerprint values assessed by the examiners in the USA are categorised as 'valid for individualisation', 'valid for exclusion', and 'no value', and such terminology is also used in published research articles dealing with the topic (Ulery *et al.*, 2013, 2014). This terminology differs from the current study which used only terms 'suitable for comparison' and 'unsuitable for comparison' when describing fingerprint usability and 'unsuitable for comparison', 'suitable for manual comparison', 'suitable for comparison using IDENT1 system' when describing quality by UK standards. If any potential future research should be more comparable with other research outcomes in this area, the change of terminology and categorisation according to the US three-way system would be beneficial. However, this change could mean that for potential examiners from countries and agencies where such categorisation does not exist currently, such as the UK, the task could appear more time-consuming and produce less accurate and or consistent assessments as a result of using unfamiliar definitions and concepts as discussed by Neumann *et al.* (2013). Whilst recommending the use of

standardised ‘difficulty scales’ agreed upon by stakeholders, current research also indicates that an adjustment in the practice of fingerprint suitability assessment would be beneficial (Eldridge *et al.*, 2020). The authors suggest that assigning suitability to fingerprints and fingermarks may be dependent on different ways in which fingerprints can be used. When initially analysing the fingerprint, the authors recommend to practitioners and researchers to create clear documentation and strategy for assessing fingerprint suitability on three levels: fingerprint value for further analysis, fingerprint complexity, and fingerprint suitability in connection to AFIS. The approach suggested by Eldridge *et al.* (2020) is one of the publications which stresses the importance of reducing inter-observer variability in experts’ assessment of fingerprint suitability which can have serious real-world consequences to the criminal justice system (U. S. Department of Justice, 2006; Campbell, 2011).

4.4.2 Quality and usability of epidermal and dermal fingerprints collected from Thiel-embalmed bodies

Fingerprint quality and usability baseline assessment showed that epidermal fingerprints were of better quality than dermal fingerprints and that there were a greater number of epidermal fingerprints deemed sufficient for comparison than in the case of dermal fingerprints. Based on the advanced age at death of the individuals who were fingerprinted in this study, this finding agrees with past studies. The studies of Chacko and Vaidya (1968), Misumi and Akiyoshi (1984), and Okajima (1979) all confirm that identifiable features on the dermal skin in elderly individuals become harder to distinguish because papillary ridges are flattened and topped with multiple branching papillae.

The fingerprint examiners who completed the analysis of the full dataset also assessed epidermal fingerprints to be of better quality and usability than dermal fingerprints. From an informal discussion or email exchange with some of the participating fingerprint examiners, the author gathered that they encountered dermal fingerprints in their casework very rarely, if ever, and therefore it is not surprising that their ability to assess dermal fingerprints and therefore judgement about the overall quality and usability of dermal fingerprints would be lower.

When comparing the baseline quality and usability assessment between fingerprints collected using powder and photography techniques, powder yielded higher quality/usability epidermal fingerprints and post-powder photography yielded higher quality/usability dermal fingerprints. The fingerprints collected using pre-powder photography were of the lowest quality and usability regardless of the skin layer when compared to fingerprints collected using the other collection techniques. This was the reason why only fingerprints collected using post-powder photography were selected for further analysis by fingerprint examiners. One of the reasons why pre-powder photography was less effective than post-powder photography could be the lack of contrast which black powder deposition on friction ridge surfaces provided for fingerprints collected using post-powder photography. The fact that the hand and digits were manipulated in between pre-powder and post-powder images taken for powder fingerprint collection could also play a role in the quality differences between pre- and post-powder photography fingerprints. The further limitation could be the insufficient lighting conditions and limited experience of the author in friction ridge image-taking from deceased individuals.

Fingerprint examiners assigned the category 3 quality (the highest) and indicated that a larger number of fingerprints were useable in the case of epidermal fingerprints collected using powder over post-powder photography which was again expected as together with inking that is the most common fingerprint collection technique when fingerprinting the deceased (Principe and Verbeke, 1973; Morgan *et al.*, 2018). Since the experts encounter in their practice epidermal powder fingerprints more often than images of friction ridge skin, this could contribute to greater confidence in assigning better quality and usability to a larger number of fingerprints collected using powder. When assessing the quality and usability of dermal fingerprints, the performance of collection techniques was more equal than in the case of epidermal fingerprints. However, a greater number of dermal fingerprints collected using powder were assigned category 3 quality than dermal fingerprints collected using post-powder photography for most of the experts (apart from the expert from New Zealand). When assessing the usability of dermal fingerprints, there was an even smaller contrast between the dermal fingerprints collected using powder and dermal fingerprints collected using post-powder photography but the majority of the

experts assigned a few more powder fingerprints as usable compared to fingerprints collected using post-powder photography.

It appears both powder and post-powder photography would be a suitable collection technique for dermal fingerprints collected from Thiel-embalmed bodies. The reduced effectivity of the powder collection technique in the case of dermal fingerprints compared to epidermal fingerprints could be explained by multiple factors. One of the biggest limitations of Thiel embalming fluid in connection to fingerprint collection is its oily nature and the fact that even after wiping off the fluid from the skin surface and the use of a drying agent (lighter fluid), the skin remained oily since the fluid continuously seeped through the pores of the dermis. Due to the oily fluid covering the dermis, only limited pressure could be applied to the skin surface during the lifting phase without causing fingerprint distortion. Moreover, the oiliness of the Thiel fluid also limited the amount of information that can be collected from each digit because full rolling or wrapping of the adhesive label around the digital pad was hard to perform without causing smudging. Since dermal fingerprints resembled more touch fingerprints rather than rolled fingerprints, it could be argued that the amount of information for fingerprint analysis was limited. Further quality limitations of dermal fingerprints collected from Thiel-embalmed bodies could be caused by a possible interference of adhesive chemicals in the label used for fingerprint lifting with those in Thiel embalming fluid. This interference is only theorised and no reference in literature was found to support this claim, however, from experience, some of the dermal fingerprint ridges lifted on the adhesive labels had a somewhat blurred appearance. Further research would need to be conducted to confirm or refute this theory. The oily nature of Thiel embalming fluid could also affect the quality of dermal fingerprints collected using photography in a way that the light reflection from fluid often obscured an area of dermal ridges limiting the amount of extractable information from a given area of friction ridge skin. More research would be needed to find a chemical agent or a technique of gently drying the seeping Thiel embalming fluid from the surface of the dermis to facilitate the collection of fingerprints with enhanced quality.

There is a possibility that the quality and usability of both epidermal and dermal fingerprints collected for this thesis would be enhanced if trained scene of crime

officers experienced in fingerprinting of the deceased and photography were to collect the fingerprints. Another factor, such as consistent lighting conditions (which were not always possible to maintain when collecting fingerprints for this thesis due to changes of the location where a body was fingerprinted in the context of daily mortuary operation requirements), could also potentially improve the quality of acquired images of friction ridge skin (Kahana *et al.*, 2001). Further technical adjustments that could potentially enhance the quality of fingerprints collected from Thiel-embalmed bodies could include the use of a single-lens reflex (SLR) camera with a tripod set up and settings allowing for the capture of the maximum surface of the digit pad in focus, and the use of powders with light colours on digits with bruising or haemorrhaging (Kahana *et al.*, 2001). Fagert and Morris (2015) weighed down the digits that were photographed with a glass pane and then used software to enhance the friction ridges. Whilst such techniques are feasible with fingerprint collection from living individuals it might be more challenging to perform on fingers of the deceased, in particular, elderly with arthritic disfiguration of interdigital joints, however, it would need to be confirmed or refuted with experimentation.

It is important to stress that although for research and fingerprint comparison purposes all measures are taken to attain the fingerprints of the highest quality possible, the environmental, circumstantial, and body conditions are not always ideal (Kahana *et al.*, 2001; Cattaneo *et al.*, 2006; Khoo *et al.*, 2016). Field conditions in DVI situations where infrastructure may be severely disrupted could potentially mean that ‘state of the art’ equipment would not be available or operational during fingerprint collection, in which case more basic fingerprint collection techniques would need to be employed (Morgan *et al.*, 2006, 2018; Black *et al.*, 2010). Therefore, the value of fingerprints collected in this study, albeit not of the best quality and with the best possible equipment, should not be dismissed.

As reported by Earwaker *et al.* (2015) initial recovery of fingerprints from deceased individuals will be the responsibility of evidence recovery experts, in Scotland scene of crime officers, known also as crime scene investigators (CSI). Therefore, they would initially decide whether or not fingerprints are of sufficient quality to be recovered for use in comparison; the final decision on fingerprint

quality will be made by fingerprint examiners once the lifted prints are submitted to the laboratory (Forensic Science Regulator, 2017c). No research was found reporting on the potential discrepancies in judgement between the quality and sufficiency of fingerprints submitted by scene practitioners and fingerprint examiners. Neumann *et al*. (2011) and Earwaker *et al.* (2015) report the discrepancies between the quality judgement of the experts who analyse and compare the fingerprints and laboratory practitioners who enhance finger marks in the US and the UK respectively but neither of the two works provides data on quality judgement discrepancies between those undertaking the fingerprint collection and analysis/comparison experts. Earwaker *et al.* (2015) at least acknowledge that there is a difference in training, working environments, policies, and procedures of evidence recovery team and fingerprint examiners. Although the experts collecting fingerprints from bodies can see the appearance of the friction ridges in the source, it does not necessarily mean this would transfer to the same quality judgement of the fingerprint as fingerprint examiner will have. According to a communication of the author with an experienced scene of crime investigator, who was active as a part of the Scottish police force, there were cases when the scene of crime officer was requested by fingerprint examiners to attend the mortuary to assess whether better quality fingerprints could be collected from the deceased, after a different scene of crime officer handed in fingerprints of insufficient quality (personal communication, G. Thomson 2020). To ensure time-effectiveness of the identification process and sufficient quality level of fingerprints collected in some major incidents such as DVI situations or incidents of terrorist attacks, UK fingerprint examiners work on-site alongside the fingerprint collection experts to provide immediate feedback on fingerprint quality (Black *et al.*, 2010; personal communication, G. Thomson 2020). It would be therefore beneficial for further research to not only consider inclusion of trained scene of crime officers in dermal fingerprint collection from Thiel-embalmed bodies, but also their on-site collaboration with fingerprint examiners at the time of fingerprint collection which would increase the potential of higher quality fingerprints being recovered from such bodies.

4.4.3 Minutiae characteristics observed in epidermal and dermal fingerprints collected from Thiel-embalmed bodies

A baseline assessment of minutiae numbers between a subsample of epidermal and dermal fingerprints collected from Thiel-embalmed bodies was conducted so it could be compared to the results from the study of Mizokami *et al.* (2015). The study of Mizokami *et al.* (2015) had a fingerprint examiner mark up and count minutiae found in 19 photographed pairs of epidermal and dermal friction ridge skin (1 cm^2) collected from deceased of unknown age at death.

Similar results to those of Mizokami *et al.* (2015) were found when comparing differences in the counts of minutiae found on dermal and epidermal fingerprints; they too found no statistical difference between the numbers of minutiae found on the epidermis and dermis regardless of fingerprint collection technique. In contrast to Mizokami *et al.* (2015), minutiae in the current study were counted in epidermal and dermal fingerprints collected using pre- and post-powder photography, and black powder; for comparison purposes between the studies, only pre-powder photography fingerprints would be comparable as Mizokami *et al.* (2015) also used this technique of fingerprint collection. For some of the fingerprint collection techniques, different tests than those employed by Mizokami *et al.* (2015) needed to be used to test the difference between the minutiae numbers of epidermal and dermal fingerprints because of the high number of fingerprints with no minutiae found on them, which could be affected by the lower quality of collected fingerprints in the current study. When comparing the results of the studies, there appear to be lower numbers of minutiae observed exclusively on the dermal skin layer and lower number of matching minutiae in fingerprints collected using pre-powder photography in the current study. However, no statistical tests were performed to test this presumption. The observed apparent difference could be present due to the low quality of fingerprints collected using pre-powder photography in this study and other possible factors mentioned above.

In contrast to the work of Mizokami *et al.* (2015), where intra-observer repeatability was not tested, intra-observer analysis of minutiae counts observed in fingerprints collected using the three different fingerprint collection techniques was performed in the current study. The excellent agreement results contrast

with the research conducted by Dror *et al.* (2011) and Swofford *et al.* (2013) who report high variation in intra-examiner analysis for fingerprint minutiae counts.

It needs to be acknowledged that the variation between the results of the studies could be attributed to various factors, the weighted effect of which was not established in the current work. The overall contributing factors influencing the differences between the results of the current study and study of Mizokami *et al.* (2015) could potentially be:

- the source of skin desquamation (Thiel-embalming versus immersion in 0.25% acetic acid solution),
- age at death of fingerprinted individuals affecting the overall quality of fingerprints (elderly versus unknown) (Chacko and Vaidya, 1968; Okajima, 1979; Misumi and Akiyoshi, 1984),
- experience and training level of assessors (no official training and limited experience versus fingerprint examiner with unknown experience) (Schiffer and Champod, 2007),
- manner of analysis (fingerprints analysed one by one to avoid bias as suggested by Dror *et al.* (2011) versus side by side comparison of epidermal and dermal fingerprint),
- subjectivity in examiners' minutiae mark-up as pointed out by numerous studies (Evett and Williams, 1996; Langenburg *et al.*, 2012; Neumann *et al.*, 2013; Ulery *et al.*, 2014).

The results of baseline analysis of minutiae numbers observed in epidermal and dermal fingerprints support the findings of epidermal and dermal fingerprint quality assessment; powder and post-powder fingerprints have more minutiae than pre-powder fingerprints which correspond with powder and post-powder photography fingerprints having a greater number of prints assigned to the higher-quality category than pre-powder photography fingerprints. Similarly, a significant difference was observed between the matching minutiae found on epidermal-dermal fingerprint pairs collected using powder and pre-powder photography (having the highest and lowest numbers of matching minutiae respectively). The observed trend is supported by the research of Neumann *et al.* (2013) and Ulery *et al.* (2013) where they found strong associations between the fingerprint quality and detected numbers of minutiae.

The author is aware of the limitations of the baseline assessment of minutiae counts detected in epidermal and dermal fingerprints collected from Thiel-embalmed bodies. Apart from the lack of formal training and absence of inter-examiner assessment of minutiae number, the number of analysed fingerprints is also limited. Since the dataset of collected epidermal-dermal fingerprint pairs is larger than the selected subsample, it would be beneficial for sounder statistical analysis and outcomes to analyse the whole dataset of available fingerprints in the future, preferably by multiple trained fingerprint examiners. Furthermore, since the photographs of friction ridge skin contain images of a curved surface where not all features around the edges are in focus, it is likely that the 1 cm^2 of fingerprints collected using photography, in reality, contains a smaller area of friction ridge detail than fingerprints collected using powder. As mentioned in the previous section, there are possibilities for capturing a larger surface of friction ridge skin from the curved surface of the finger pad that could be explored in any future potential experiments (Kahana *et al.*, 2001; Fagert and Morris, 2015). If this study should be repeated by other researchers, it would be also beneficial to test repeatability and reproducibility of the method used for selecting the area of interest. The repeatability and reproducibility assessments were not conducted in this study due to time constraints and this is also acknowledged as a limitation that could have an impact on the results.

The assessment of epidermal and dermal fingerprints for the presence of minutiae characteristics could not be directly compared between the experts from the countries who took part in the research due to their two different approaches to fingerprint analysis. The division of minutiae number ranges was first established after a conversation with the UK experts who work according to the non-numeric/holistic approach. The experts from Sweden and New Zealand also follow the holistic fingerprint analysis approach and used the same minutiae number ranges in the fingerprint assessment for this thesis. The experts from Belgium use the numeric approach of fingerprint analysis where a minimum of 12 matching minutiae is required for identification, therefore their minutiae number ranges were adapted accordingly. Since the minutiae number ranges overlap each other between the two groups of experts not all minutiae number ranges are directly comparable. The only minutiae number ‘range’ that can be directly

compared between the two groups of experts is a zero-minutia-detected. The percentage of fingerprints where no minutiae could be identified was greater for Belgian than the rest of the experts in all categories of fingerprints (grouped by skin layer and collection technique). It could be theorised that because the numeric system is dependent on a certain number of minutiae to be present on both compared fingerprints to establish an identification, the experts might be operating with the threshold to reach in mind, and in cases where the fingerprint appears to be of low quality and it is unlikely that the threshold would be reached, less effort might be made to identify a few potential minutiae that would be of very limited value to them. However, it is still only untested speculation since no previous research was found that discussed the differences in minutiae detection techniques and differences in judgement in connection to numeric versus holistic fingerprint analysis approach. The closest to discussing the issue was the report of Evett and Williams (1996) where it is mentioned that the UK fingerprint examiners working under the 16-point numeric threshold had tendencies to take part in 'teasing out' the minutiae in the unknown mark/fingerprint when sidewise comparison with the reference fingerprint was performed; instead of undertaking a full analysis and extensive mark-up of the unknown element, the experts would only try to find the corresponding minutiae they identified in the reference print.

Regardless of the numerical/holistic approach to fingerprint analysis, the percentages of fingerprints with no minutiae identified in them were higher for dermal fingerprints compared to epidermal fingerprints, equal between the collection techniques for dermal fingerprints and higher for epidermal fingerprints collected by post-powder photography than epidermal fingerprints collected using powder. Both groups of experts detected on average the largest minutiae number in epidermal fingerprints collected using powder, followed by epidermal fingerprints collected using post-powder photography. For dermal fingerprints, the interesting finding was that, in both expert groups, the percentage of detected minutiae was equal when comparing the two fingerprint collection techniques. The results of detected minutiae suggest a trend similar to the trend observed in the results from experts' fingerprint quality assessment. As with the baseline minutiae assessment, the similar trends found in minutiae detected and fingerprint quality assessment suggest an association between the fingerprint

minutiae counts and quality determination (Neumann *et al.*, 2013; Ulery *et al.*, 2013).

To further investigate the association between the number of minutiae detected and quality assessment of epidermal and dermal fingerprints, consistency scores were calculated for each expert within each category of the skin layer and fingerprint collection technique. The consistency scores were numbers of fingerprints that had the same category number for both – minutiae and quality – assigned by all of the experts (the 'zero' minutiae number 'range' was merged with the minutiae number range 1, between 1 and 7 minutiae, to facilitate the corresponding number of categories). Two of the Belgian experts who use the numerical approach had full or almost full consistency scores for all groups of fingerprints (epidermal, dermal, fingerprints collected using powder and post-powder photography), which was not surprising as their fingerprint quality analysis categories and minutiae ranges were adjusted from the original UK-based template to reflect the analysis stage of ACE process employed in Belgium. The adjustment of quality categories and minutiae ranges were performed because the Belgian fingerprint quality assessment relies on finding the threshold number of minutiae (12) in a fingerprint for it to be deemed compatible with the possibility of identification outcome. The relative consistency in the scores could be affected by them working at the same agency, following the same training and standards. The association between minutiae counts detected in fingerprints and fingerprint quality assessment present in the two experts is in keeping with findings from other studies (Neumann *et al.*, 2013; Ulery *et al.*, 2013).

More surprising is that even though quality categories were very closely corresponding to the minutiae number ranges, the other two Belgian experts had low consistency scores with the number of misclassified fingerprints reaching 52.5% of fingerprints (mainly for dermal fingerprints and fingerprints collected using post-powder photography). The inconsistencies could be caused by mistakes during filling in the answer sheet or they could be a result of possible insufficient instructions before participation in the project. This also stresses the subjectivity of fingerprint analysis and the importance of the ACE-V verification step implementation in future studies which could highlight the differences in

opinion between minutiae detected by various experts and bring attention to more challenging fingerprints (Ulery *et al.*, 2013). The verification step was omitted from the procedure during epidermal-dermal fingerprint analysis performed by the experts to cut down on the time the experts would spend working on the fingerprints to increase the probability of their participation upon recruiting.

Consistency scores calculated for the group of experts working according to the holistic fingerprint analysis approach were not calculated as they would not describe the true association between the fingerprint quality and the number of minutiae detected in a fingerprint because a minimum of eight minutiae required for a fingerprint to be assigned quality category 3 in the UK and New Zealand also means that a fingerprint with 8 minutiae detected (or 6 for the experts from New Zealand) could belong to the UK/New Zealand minutiae number range 1 causing an 'inconsistency' in the consistency scores. Similarly, Swedish experts were excluded from the calculations as they have only two quality categories.

The agreement in experts' minutiae detection was what the current literature considers, a good level, when taking into consideration the 95% confidence interval for all groups of experts analysing epidermal fingerprints and for almost all groups of experts when analysing fingerprints collected using powder (apart from Belgium experts) (Krippendorff, 2013). Agreement in minutiae assessment was not at a good level for dermal fingerprints and fingerprints collected using post-powder photography for all groups of experts. A true statistical difference was found in experts' agreement between the epidermal and dermal fingerprints in all groups of experts. This agrees with previous research about the higher rates of inconsistencies between experts when analysis of more complex or low-quality fingerprints is undertaken (Hicklin *et al.*, 2013; Ulery *et al.*, 2013), since the quality of dermal fingerprints collected from Thiel embalmed cadavers and dermal fingerprints, in general, was shown to be lower and minutiae characteristics harder to detect (Okajima, 1979; Misumi and Akiyoshi, 1984; Mizokami *et al.*, 2015).

A statistical difference was found in experts' agreement between the minutiae counts in fingerprints collected using powder and photography for all expert groups from the countries with a holistic approach. All groups of experts but the

experts from Belgium had better agreement levels for fingerprints collected using powder. It is unclear why there was no difference observed in the agreements of Belgian experts. The differences in minutiae detection agreements for fingerprints collected using different collection techniques again suggests the experts are more confident in, and used to working with, fingerprints collected using the powder in contrast to images of friction ridge skin (also epidermal fingerprints over dermal fingerprints) (personal communication, B. Robertson 2018).

Even the ‘good’ levels of agreement are not excellent and multiple studies show there is substantial inter- and intra-examiner variation in minutiae counts observed in fingerprints (Evett and Williams, 1996; Schiffer and Champod, 2007; Dror *et al.*, 2011; Langenburg *et al.*, 2012; Ulery *et al.*, 2014). The factors introducing discrepancies are numerous and besides the abovementioned quality levels (the lower the quality of the fingerprints recovered, the more demanding and subjective the analysis process will be), Schiffer and Champod (2007) and Neumann *et al.* (2013) mention the importance of unified definitions and understanding of basic minutiae concepts, clear guidelines and structured approach to the examination as essential to increase the consistency in fingerprint assessment. Further potential contributors to the lessened inter-expert agreement on minutiae counts detected in fingerprints could be differences in equipment or software used for analysis in the current study (fingerprints comparators versus analysis of digital images on computer screens with fingerprints of different resolutions and different types of comparison software employed). Apart from securing access to the same pieces of equipment with the same clear sets of instructions and understanding of main concepts, the article by Smith (2019) suggests inclusion of more complex and low-quality fingerprints into the training exercise for the experts to further limit the discrepancies in experts’ agreement when analysing fingerprints.

4.4.4 Comparison of epidermal and dermal fingerprints collected from Thiel-embalmed bodies

The experts reported a greater number of correct exclusions than correct identifications from among those epidermal-dermal fingerprint pairs which were successfully identified or excluded. The greater number of correct exclusion comparison outcomes than identification comparison outcomes was made

regardless of the fingerprint collection technique. In comparison to the study performed by Mizokami *et al.* (2015), there were slightly over twice the number of fingerprints being compared in this study. In comparison to the identification outcomes of Mizokami *et al.* (2015), the proportion of epidermal-dermal fingerprint pairs that did not yield identification or exclusion outcome was much larger in the current study. Mizokami *et al.* (2015) report that identification (the study contained only matched fingerprint pairs) was possible in 16 out of 19 cases, which gives 15.8% of cases where identification could not be confirmed. In the current study, there were on average between 42.9% and 70% of fingerprint pairs which could not be identified or excluded for fingerprints collected using powder and between 37.5% and 82.5% of fingerprint pairs which could not be identified or excluded for fingerprints collected using post-powder photography. It needs to be reiterated that the lower quality of fingerprints collected from elderly individuals as fingerprint donors in this study does limit the extent to which the results can be extrapolated to the population of epidermal-dermal fingerprint comparison typically encountered in casework. As the age at death of subjects fingerprinted in the study of Mizokami *et al.* (2015) was unknown, the comparison between the different datasets within the context of fingerprint quality related to age is impossible. It further needs to be acknowledged that although there is a possibility for a recovery of a single digit from a crime scene or DVI situation with severe fragmentation of victims, the experts will rarely have cases where only one dermal and one epidermal fingerprint would be present for comparison (personal communication, J. Scott 2018). Moreover, in real-life situations, it is highly likely the experts would be comparing post-mortem set of fingerprints with a number of ante-mortem sets from multiple candidates which is a complexity of fingerprint identification process omitted from the method of current study due to the time constrains. Therefore, the work done by the experts as a part of the current study might not necessarily be representative of decisions that would have been made in the case of 'real-life' casework in which the process used and information available may differ.

In contrast to the findings of Ulery *et al*. (2012) who report six false identifications made by examiners within their study (all of which were identified by a verification process), there were no false identifications reported by the experts when comparing epidermal and dermal fingerprints from Thiel-embalmed bodies. The

absence of false identifications is a positive sign in this case, however, it is important to acknowledge that the experts were only dealing with one-to-one fingerprint comparison in this study when they did not have to go through a list of ante-mortem fingerprint candidates suggested by an AFIS search. Such procedure would better reflect the operational practice but is also more prone to false identification, as suggested by Dror *et al.* (2012). In contrast to false identifications in this study, false exclusions were made by the experts after comparison of epidermal and dermal fingerprints collected from Thiel-embalmed bodies. Ulery *et al.* (2012) report a total false-exclusion rate of 8.8% after experts compared latent fingerprint marks with reference fingerprints. The false-exclusion rates in this study ranged between 2.5% and 20% for individual experts. Presence of no false identification, but numerous false exclusions suggests that the experts appear to err on the side of caution. Worth noting also is that the expert with the highest rate of false exclusions was the UK expert who did not have access to a fingerprint comparator. Even though it is only one expert and the lack of equipment might not be the only factor influencing the comparison outcomes, it suggests that access to better equipment might contribute to more favourable fingerprint comparison outcomes. A limitation of this part of the study is the lack of the verification part in the ACE-V process of epidermal-dermal fingerprint assessment. As suggested by the work of Ulery *et al.* (2013) the verification step is an important part of the quality assurance during fingerprint comparison. However, as it is shown by the work of Ulery *et al.* (2012) even after the verification process, 30% of the false exclusions were repeated by the fingerprint examiners. To minimise the variations of expert outcomes, as well as minimise false identifications and false exclusions, besides blind verification Ulery *et al.* (2012) recommend including targeted quality control in case of complex finger marks/fingerprints, a collaborative examination of such fingerprints, the involvement of the ‘difficult’ fingerprints in training, and implementation of procedures for detailed documentation of the features. The author does not know how many of these are already part of the standard operating procedures in agencies who examined the fingerprints for the current study, but they are all relevant for implementation in cases of epidermal-dermal fingerprint comparison.

In an attempt to simplify the summary of comparison outcomes reported by each fingerprint examiner after examination of epidermal and dermal fingerprints from

Thiel-embalmed bodies, accuracy percentages were calculated for experts who completed the dataset for at least one of the datasets within the collection technique category. Some of the inconclusive fingerprint comparison outcomes were included in the calculations of accuracy, namely in cases where all experts agreed on the outcome for given epidermal-dermal fingerprint pair. According to Dror and Scurich (2020), it is crucial to include correctly assigned inconclusive comparison outcomes into calculations of fingerprint comparison error rates. One of the way in which correctly assigned inconclusive comparison outcome can be established is to include cases where all of the experts agreed on such assignment of comparison outcome. This was applied also in the current study. Even though the inclusion of correct inconclusive outcomes increased the individual expert accuracy percentages (as opposed to including only correct exclusion and identifications), the highest accuracy was 85% in case of New Zealand expert analysing fingerprints collected using post-powder photography. This expert anecdotally mentioned having considerable experience in analysing dermal fingerprints as a part of casework, which could have an impact on their performance and highest individual accuracy percentages. Considering potential social implications of experts arriving at an incorrect fingerprint comparison outcome (incorrect exclusion when a person was supposed to be identified or missed identification), the experts performed with relatively low accuracy when comparing epidermal-dermal fingerprint pairs from Thiel-embalmed bodies (Dror and Langenburg, 2019; Dror and Scurich, 2020). It is likely that the generally low quality of fingerprints provided for experts' analysis, as well as the limited experience of working with dermal fingerprints in the majority of the experts could have an effect on experts' performance in comparison of epidermal-dermal fingerprint pairs collected from Thiel0-embalmed bodies.

The number of cases in which the fingerprint examiners went ahead with fingerprint comparison and came to an outcome of exclusion or identification despite deeming at least one of the fingerprints as unsuitable for comparison, was calculated for each expert to investigate how consistent the experts are in fingerprint usability assessment with regards to comparison outcomes. One would expect that if at least one fingerprint from the compared pair is unsuitable for comparison the experts would not continue with the fingerprint examination process, although cases where fingerprint examiners adjust their initial usability

assessment are common (Neumann *et al.*, 2013; Ulery *et al.*, 2015). In the current study, there were more cases of exclusions than identifications found in which at least one of the fingerprints was classified as unsuitable for further comparison. In the case of exclusion outcome, one discrepancy between the two compared fingerprints is sufficient (Expert Working Group on Human Factors in Latent Print Analysis, 2012). Therefore, it appears that with fingerprints of lower quality, such as epidermal and dermal fingerprints collected from elderly individuals, caution needs to be exercised with identifying fingerprint pattern types, and minutiae characteristics and presence in general (Chacko and Vaidya, 1968; Okajima, 1979; Misumi and Akiyoshi, 1984; Mizokami *et al.*, 2015). Albeit this study was performed on a sample with limited number of experts and without the step of verification, findings of discrepancy in the experts' analysis workflow raise societal concerns about the fingerprint identification process currently performed by the fingerprint examiners especially in the case of low-quality fingerprints (Tully, 2019; Eldridge *et al.*, 2020; Nic Daeid *et al.*, 2020). There is a possibility that the experts did not record their actions accurately and after changing their opinion would omit to make the change in the answer sheets. Another possibility which could affect the differences in usability assessment of fingerprints and comparison outcome is if the experts assessed the overall fingerprint quality and then during further fingerprint analysis of side-to-side comparison they found a localised area of better quality which was used for the comparison (Hicklin *et al.*, 2013). Potentially the experts might interpret the term 'insufficient for comparison' as insufficient for identification but sufficient for exclusion, which would explain the times when the fingerprints were used for exclusion but not those fingerprints still used for identification. This explanation for discrepancies found in the current study could be a part of a larger problem where there is a lack of consistency in understanding the concepts of sufficiency and fingerprint quality (Neumann *et al.*, 2013). There could also be a misunderstanding of the procedure (or insufficient explanation of) where the experts would feel obliged to try comparing the fingerprints despite their initial judgement of the unsuitability of the fingerprints. In any future studies, it would be suitable to re-evaluate the instructions given to the experts and make every effort to make them clear, and to add a detailed structured protocol with steps that are easy to follow (Schiffer and Champod, 2007). Further consideration that should be given in any future research is doing a full-scale ACE-V comparison of epidermal and dermal fingerprints where there

is a likely possibility that the verification step would eliminate discrepancies between quality/usability assessment and comparison outcome (Ulery *et al.*, 2013).

The only expert who was fully consistent (out of those who completed the analysis of the full dataset) and had zero identifications and exclusions where at least one of the fingerprints from the pair would be deemed unsuitable for comparison was Swedish expert J. Although they are only one expert and no generalisations can be extrapolated from this case, it would be interesting to investigate whether the way of 'linear ACE' fingerprint analysis could influence higher consistency between fingerprint usability and comparison outcome. The linear ACE analysis encompasses the same processes as 'classic' ACE fingerprint analysis with the difference being in the solitary analysis and mark-up of the unknown finger mark/fingerprint before its comparison with the reference fingerprint; any changes that occurred between the analysis step and comparison should be accompanied with detailed information (Ulery *et al.*, 2015). As was proven by Fraser-MacKenzie *et al.* (2013) the side-to-side analysis and comparison of fingerprints (utilised by all but Swedish experts participating in the current study) and undocumented changes to minutiae mark-up can create a higher chance for examiners to arrive at incorrect and biased comparison outcomes. The same authors report that the knowledge of another examiner deeming a fingerprint unsuitable meant that other examiners were more likely to also assess the fingerprint as unsuitable, which could also affect the discrepancies between the usability assessment and comparison outcomes of epidermal and dermal fingerprints. The effects observed by Fraser-MacKenzie *et al.* (2013) were weaker in the group of experts who were certified by International Association for Identification and the authors suggest training might reduce the effect of contextual influence and bias in fingerprint suitability determination (Dror and Charlton, 2006; Dror and Rosenthal, 2008; Dror *et al.*, 2012).

Expert agreement in epidermal-dermal fingerprint comparison outcomes was assessed based on two different groupings: five-way and three-way comparison outcomes. The five-way comparison outcomes contain the full variety of 'inconclusive' and the answers reported by the experts were kept in original format as they were recorded in the answer sheets. The three-way comparison

outcomes contained all the answers where the fingerprints were essentially not good enough to deem identification or exclusion pooled together into one category.

In the first instance of five-way comparison outcomes, there was no statistically significant agreement found between experts' comparison outcomes in any of the groups of experts for any of the skin layer and fingerprint collection categories. As reported by Langenburg (2009) and Ulery *et al.* (2012, 2011), this supports the findings that fingerprint examination and comparison is very subjective. The lack of agreement between the experts could also be explained by the fact that there are three different outcomes which are not identification or exclusion. Experts from some countries/agencies were not familiar with the comparison outcome 'unable to exclude' since it is not in use in their countries/agencies; even in the UK such an outcome is reported only in the case of DVI situations (personal communication, J. Scott 2018). Since the fingerprint examiners from Belgium, Sweden, and New Zealand are not familiar with the term, the 'unable to exclude' comparison outcome is likely misrepresented in the current results. There is also a discrepancy between the reporting of 'insufficient' and 'NA' comparison outcomes by the UK fingerprint examiners. Technically, the 'insufficient' term is used in practice in cases where the comparison takes place, but the results are inconclusive, and 'NA' would be a suggestion that the comparison did not even take place due to the low quality of the fingerprint/s. For the simplification of the method, in this case the experts were asked to note down all of 'NA' cases as 'insufficient'; some of the experts did it and some went ahead with the system of 'NA'. This likely created a discrepancy in the agreement results even for the experts who were from the same country/agency. The limitation was most likely caused by unclear directions and based on the present experience should not be repeated in any further studies.

When the comparison outcomes of all but expert Q were pooled, a statistically significant difference between the agreements in comparison outcomes was found when comparing fingerprint collection techniques. The difference in the agreement is in favour of the powder collection technique when analysing the three-way fingerprint comparison outcomes. In the case of the five-way comparison outcomes, a statistical difference between the experts' agreement in

comparison outcomes of fingerprints collected using the two techniques was present only in the analysis of Belgian experts in favour of powder fingerprints. As was already discussed in the sections above, this could be an effect of the higher quality of fingerprints collected using powder combined with the fact that the experts are more frequently working with fingerprints rather than with photographs of digits with friction ridge skin (personal communication, J. Scott 2018).

In the instance where all inconclusive outcomes (reported as insufficient, NA, and unable to exclude) were pooled into one category and a total of three comparison outcome categories were compared, the agreement of the experts appeared to increase in comparison to the previous set up. However, a good level of agreement was found only in the case of UK experts (without expert Q) regardless of the fingerprint collection technique. This could be due to the fact that reporting of comparison outcomes for this experiment was set up according to the standards followed by the Scottish fingerprint examiners. Although it needs to be stressed that the author's familiarity with internal standard operating procedures in fingerprint examination was limited as these are not accessible to the public, a discussion with fingerprint examiners who described the process helped to outline the major steps. The subjectivity of experts' opinions in reporting of epidermal-dermal fingerprint outcomes remained, especially when pooling all experts into one category. Despite the best efforts of the author to gain an understanding of fingerprint examination processes for each group of the experts, the discussions that were had with the experts appeared to have been insufficient for devising a more inclusive experimental design that would have customised a set of instructions for each group of experts. It is the author's opinion that such instructions would lead to a more coherent set of answers provided by the fingerprint examiners who participated. A further factor that could have an influence on inconsistencies in experts' agreement in terms of fingerprint comparison outcomes could be the aforementioned differences in styles of analysis and comparison (side-by-side analysis and comparison versus the sole analysis of the 'unknown' dermal fingerprint followed by the comparison with carefully documented changes in the mark-up of the 'unknown' print) (Expert Working Group on Human Factors in Latent Print Analysis, 2012; Kassin *et al.*, 2013). As suggested by Dror *et al.* (2011) the presence of both fingerprints

(unknown and known source) affects the features observed in the latent (unknown) mark/fingerprint which could affect resulting comparison outcome, especially in the presence of poor-quality epidermal and dermal fingerprints.

A moderate positive correlation between the years of experts' experience and the number of correctly identified and excluded fingerprint pairs suggests that the experience of the experts could be one of the factors that influence the decision making processes during epidermal-dermal fingerprint analysis and comparison (Schiffer and Champod, 2007). In the current study, with increasing numbers of years of expert's experience, there was an increase in numbers of correctly identified and excluded individuals based on the comparison of epidermal-dermal fingerprint pairs collected using powder but not post-powder photography, which could be again caused by the fact that the experts are more familiar with analysing and comparing fingerprints rather than photographs of digits with friction ridge skin (Khoo *et al.*, 2016; Morgan *et al.*, 2018). The sample size is a limitation not only for this analysis, but the whole part of the current study in which fingerprint examiners were involved. For this particular section, the small sample size limitation was even more obvious, as the number of experts who completed the analysis of the whole dataset as well as reported the number of years of experience in fingerprint analysis was smaller than the number of participating fingerprint examiners. Future research into the comparison of epidermal and dermal fingerprints would largely benefit from a larger sample size of experts, but according to the experience of the author, it would require a larger timescale and greater motivation for the experts to participate. In their study Fraser-MacKenzie *et al.* (2013) state that it is infamously difficult to gain access to the UK fingerprint community. Even more accurate comments about the difficulty to gain participants from the world-wide fingerprint examiners community came from a fingerprint examiner who communicated that asking to perform voluntary tasks from a community of over-worked and under-paid professionals will often meet with little interest in participation (personal communication, C. Gibb 2020).

4.4.5 Future research

Apart from adjusting all the adjustable limitations mentioned during the discussion, there are new branches of this project that could be explored on various levels. Further exploration of fingerprint collection from Thiel-embalmed

bodies could involve experiments employing adjusted collection techniques, such as photography using adhesive scales and camera settings that would allow for photographing of thumbs as well as capturing of the curved surface of digits. Further collection techniques such as casting, staining, or use of powders that would provide better contrast with dark skin (naturally darker, bruised, haemorrhaged) could be explored in connection to the collection of fingerprints (epidermal and dermal) from Thiel-embalmed cadavers. A collection technique that is used in a limited capacity on deceased individuals is a digital capture of friction ridge characteristics via scanning devices. As Johnson and Riemen (2019) report successful identifications with the use of their device in the field (DVI situation), it would be in the interest of possible future research to also test this device for collection of dermal fingerprints from Thiel-embalmed bodies. Further advances in digital capture of fingerprints of deceased, such as a non-touch 3D scanner and virtual 3D modelling techniques could also be tested in order to increase the quality of friction ridge skin dermal layer captured in Thiel-embalmed bodies (Mulawka and Troy, 2016; Panetta *et al.*, 2019).

Furthermore, dermal fingerprints collected by trained scene of crime examiners could be used in potential future research to find out whether the quality of dermal fingerprints collected from Thiel-embalmed bodies would increase. Moreover, as was mentioned in section 3.4, further investigation in the timeframe of epidermal desquamation in Thiel-embalmed bodies would help with the planning of any potential experiments involving dermal fingerprints collected from Thiel-embalmed bodies.

On the level of fingerprint analysis and comparison, complementary/corroborative use of both dermal fingerprints collected using powder and photography could be supplied to fingerprint examiners to estimate whether more information could be extracted for identification purposes and whether the corroboration of both dermal fingerprints would create a greater chance for an individual to be identified.

Future research could also explore experts' minutiae mark-up on epidermal and dermal fingerprints, to monitor not only the number of minutiae detected in the fingerprints and their spatial relationships but also any minutiae found exclusively on either of the fingerprints as it was conducted in the study of Mizokami *et al.*

(2015). In further steps of observation, any changes made to minutiae mark-up during the comparison stage of fingerprint examination could also be documented (Ulery *et al.*, 2015).

To further explore the applicability of epidermal-dermal fingerprints research to forensic practitioners, it would be interesting to provide a mixture of full ten-print (one fingerprint collected from each hand digit of an individual) dermal sets and multiple fingerprints from each individual's epidermal skin layer to fingerprint examiners. The goal would be for them to perform a full examination of fingerprints simulating a potential DVI situation, where the examiners must analyse post-mortem fingerprints (dermal sets), ante-mortem fingerprints (some of the epidermal fingerprints), and perform a comparison of both sets to provide an identification or exclusion outcome. Interesting for further research that would be more applicable to fingerprint examiners would be also the inclusion of the verification step into the examination and comparison of epidermal and dermal fingerprints collected from Thiel-embalmed bodies.

To complement the comparison between dermal and epidermal friction ridge skin of deceased individuals, collection and comparison of palm and foot sole prints from Thiel-embalmed bodies could be explored as a possible future research avenue. A number of epidermal and dermal fingerprints were collected from bodies before and after Thiel-embalming, but they were not included in the current study due to the time constraints of the author and fingerprint examiners.

Apart from testing the digital collection of dermal fingerprints, it could be beneficial to test the performance of an AFIS system when dealing with a repository of epidermal and dermal fingerprints collected from Thiel-embalmed bodies. It would be interesting to observe how well the system performs when searching epidermal fingerprints entered into the system as ante-mortem data and dermal fingerprints entered as post-mortem data of an unknown body.

Chapter 5 General discussion and conclusions

Exposure of the dermis in friction ridge skin of Thiel-embalmed bodies was a result of epidermal desquamation that occurs during the immersion of most bodies in Thiel-embalming fluid. The exposure of dermis was confirmed in 17 out of 20 observed cases to occur within the first four weeks of immersion in Thiel embalming fluid. For fingerprint identification research, the current pilot study into epidermal desquamation confirmed the possibility of studying epidermal and dermal fingerprints from the same individuals without the need for further chemical treatment of digits and/or removal of digits as was done in all previous studies concerning the study of dermal fingerprints (Plotnick and Pinkus, 1958; Chacko and Vaidya, 1968; Okajima, 1979, 1984; Misumi and Akiyoshi, 1984; Mizokami *et al.*, 2015).

It is important to acknowledge that during the first six weeks of body immersion in Thiel embalming fluid, there were a few cases in which epidermal desquamation was observed in histological friction ridge samples to occur only between the layer of keratinised and non-keratinised epidermis which would suggest that the dermis was not fully exposed in the friction ridge skin in these few cases. Moreover, in a few cases unrelated to histological study, it was also observed macroscopically that despite the termination of body immersion in embalming fluid and completion of the embalming process, epidermal desquamation between the epidermis and dermis did not occur in extremities and digits. More rigorous research needs to be conducted to better understand the nature and timeframes of epidermal desquamation in Thiel-embalmed bodies, especially why in some cases epidermal desquamation might not occur.

In those Thiel-embalmed bodies where the epidermal desquamation between the epidermis and dermis of friction ridge skin did occur, it allowed for such bodies to be model subjects for the collection of dermal and epidermal sets of fingerprints. Sets of epidermal and dermal fingerprints were collected using black powder and photography. Collection of fingerprints from bodies before and after they were embalmed proved to be challenging due to the advanced age of the bequeathed individuals and the oily nature of Thiel embalming fluid. However, sets of epidermal and dermal fingerprints from 67 bodies were collected. Based on the

fingerprint quality and usability results, the powder collection technique appeared to be a more successful method for epidermal fingerprint collection of elderly deceased individuals than photography. For the collection of dermal fingerprints that have high enough quality for comparison purposes, both techniques – black powder as well as photography after the lifting of powder prints, could be recommended. The quality of dermal fingerprints collected from Thiel-embalmed bodies of elderly deceased individuals was lower in comparison to their epidermal counterparts. Factors influencing the quality of collected dermal fingerprints in this study could be the oily nature of Thiel embalming fluid and its possible interference with adhesives in lifting labels, and manual scrubbing of Thiel-embalmed bodies to prepare them for dissection. Factors affecting the quality of both, epidermal and dermal fingerprints in the current study, could be the training and experience levels of the person collecting the fingerprints, age, and occupation of deceased individuals and any unknown pathologies. Therefore, finding a suitable collection technique which would make the most of these challenging fingerprints is essential. Although more fingerprint collection techniques should be tested on Thiel-embalmed bodies to explore the best way of fingerprinting epidermal and dermal friction skin layers of elderly individuals, it is encouraging to confirm that relatively low-cost solutions such as black powder combined with white adhesive labels and photography could be employed in situations when access to more elaborate equipment might be limited because of infrastructure damage or restricted access to financial resources (Morgan *et al.*, 2006, 2018).

Expert analysis and comparison of fingerprints that originate from the same epidermal layer of friction ridge skin has its own set of challenges, especially in cases of finger marks and fingerprints of poor quality, as was proven by multiple studies to date (Dror and Charlton, 2006; Dror and Rosenthal, 2008; Dror *et al.*, 2011; Fraser-MacKenzie *et al.*, 2013; Kassin *et al.*, 2013). Based on the results of epidermal-dermal fingerprint comparison performed by fingerprint examiners in the current study, comparison between the fingerprints from the dermal and epidermal friction ridge skin layer poses its own sets of challenges that are possibly connected to the quality of fingerprints, age of the deceased individuals, and examiners' prior experience of working with dermal fingerprints. Even though the small sample size of fingerprints analysed by a small number of fingerprint

examiners limit the interpretation of findings, when compared to other published studies, the current results also suggest the presence of subjectivity and inconsistencies in the experts' assessment of epidermal and dermal fingerprint quality and sufficiency (in the current study usability) assessment, minutiae detection, and in the reporting of comparison outcomes (Dror *et al.*, 2011; Ulery *et al.*, 2011, 2012, 2013, 2014, 2015; Swofford *et al.*, 2013). A promising way to deal with the lack of experts' reproducibility and repeatability in fingerprint quality assessment could be algorithms which provide objective user-independent assessment of fingerprint quality and suitability for further analysis (Tabassi *et al.*, 2013). This study further proved that the identification and exclusion of individuals based on the comparison of epidermal and dermal fingerprints collected from elderly individuals is possible. Contrary to other studies which compared only epidermal finger marks and fingerprints, there were no false identifications reported by the fingerprint examiners when comparing epidermal and dermal fingerprints collected from Thiel-embalmed bodies. To the best of the authors knowledge, this is the first study in which fingerprint examiners compared matched and unmatched epidermal-dermal fingerprint pairs in contrast to Mizokami *et al.* (2015), where experts only compared matched epidermal-dermal fingerprint pairs, therefore no comparison with other similar studies was possible. However, there were some false exclusion comparison outcomes and a high number of 'inconclusive' comparison outcomes in the current study. Although it could be argued that the implementation of the verification step of the ACE-V fingerprint examination process could have prevented the false exclusions, caution is advised when a comparison of epidermal and dermal fingerprints is performed for identification purposes of bodies, similarly as suggested by Mizokami *et al.* (2015). Caution is especially advised for identification of body fragments based on the comparison of epidermal and dermal fingerprints where only one digit was available for fingerprinting post-mortem (relevant for DVI situation with fragmentary remains such as flight disasters and terrorist attack incidents).

The results of experts' analysis also support the fact that fingerprint examiners work more frequently with epidermal fingerprints over dermal fingerprints, and also more frequently with impressions of friction ridge skin (fingerprints) rather than images of the friction ridge skin surface of digits. The current project did not

study to what extent the experts' limited experience of working with dermal fingerprints and fingerprints collected using photography could influence the results. However, as suggested by Ulery *et al*. (2012), one of the ways to increase consistency in fingerprint examiners' performance is to provide training tools, such as challenging and rarely encountered fingerprints, that would enhance experts' experience before they are faced with similar challenges as a part of their casework. Fingerprints collected for the purposes of the current study will be used to design this training resource.

In conclusion, Thiel-embalmed bodies offer a valid opportunity to study epidermal and dermal fingerprints collected from the same source. This study suggests that the collection, analysis, and comparison of epidermal and dermal fingerprint pairs should be approached by fingerprint examiners with caution, especially in cases where the fingerprints are collected from elderly individuals. The author acknowledges the need for further research in the area of epidermal and dermal fingerprint comparison, and the need to include more dermal fingerprints into the training of fingerprint examiners. Therefore, epidermal and dermal fingerprints collected from Thiel-embalmed individuals for this study will be used to create a ground truth database of epidermal and dermal fingerprints that will be made available for fingerprint examiners interested in enhancing their experience of epidermal-dermal fingerprint comparison and researchers studying relevant topics. To further disseminate the potential of Thiel-embalmed bodies in the research of epidermal and dermal fingerprints, publication of results from the current study in peer-reviewed journals is also planned (Appendix 11).

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Appendix 1 Image capture permission

IMAGE CAPTURE PERMISSION

Please complete this form before photographing cadavers in the Dissecting Room and lodge form with Vivienne McGuire or Gillian Malone in the Centre Office

Thank you

Vivienne McGuire
Bequest Administration

Date:	17.01.2019
Name of Photographer:	VERONIKA DZETKULIČOVÁ
Cadaver No:	See attached.
Description of Image Capture:	HANDS
Name of Licenced Teacher:	S. SKENG
Signed by Licenced Teacher:	

UNIVERSITY OF DUNDEE

Centre for Anatomy & Human Identification

IMAGES OF HUMAN TISSUE

As a licensed anatomical facility, we are governed by the Anatomy Act (1984) and the Human Tissue (Scotland) Act (2006), which allow storage of human tissue for anatomical examination. The fundamental principle behind this use of human tissue is ***consent***, and all our donors have fully consented to the procedures undertaken in our Centre. Naturally we rely on the continuing goodwill of the donors and their families in order to provide this form of anatomical education, and cannot thank them enough for their generosity and selflessness. It is therefore extremely important to us that we do not allow human tissue to be used for any purpose for which informed consent has not been expressly given.

Please would you read through, and adhere to, the following rules of conduct relating to the use and dissemination of images of human tissue:

- Images of human tissue can only be used for teaching, educational or research purposes
- Publication or distribution of images, including art, is strictly prohibited
- Dissemination of images must not be disseminated in any form of social media or any other format that is accessible by the public

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Declaration

I confirm that I have read and understood the above rules of conduct and I agree to abide by them.

Name (please print full name in block capitals):
VERONIKA DZETKULIČOVÁ

Date: 17.01.2019

Signature: V Dzetkuličová

Cadaver No	Date out of the tank
1409	09/08/2018
1410	09/08/2018
1411	18/09/2018
1412	12/10/2018
1416	22/10/2018
1417	22/10/2018
1418	19/10/2018
1419	22/10/2018
1422	22/10/2018
1423	22/01/2019
1424	15/01/2019
1425	16/10/2018
1429	19/12/2018
1430	22/10/2018
1431	22/10/2018
1432	03/01/2019
1433	26/10/2018
1434	04/01/2019
1435	03/01/2019
1437	16/01/2019
1442	15/01/2019
1445	05/02/2019
1447	05/02/2019
1448	07/02/2019
1449	13/02/2019
1450	25/02/2019
1453	11/03/2019
1454	14/03/2019
1455	19/03/2019
1456	22/03/2009
1457	01/04/2019
1458	02/04/2019
1459	03/04/2019
1460	08/04/2019
1461	25/04/2019
1462	30/04/2019
1463	03/05/2019
1464	08/05/2019
1466	13/05/2019
1468	20/05/2019
1469	22/05/2019
1470	22/05/2019
1471	27/05/2019
1473	24/06/2019
1474	02/07/2019
1475	02/07/2019
1476	02/07/2019
1477	09/07/2019
1480	24/07/2019

1481	25/07/2019
1482	26/07/2019
1483	31/07/2019
1484	31/07/2019
1485	21/08/2019
1486	13/08/2019
1487	29/08/2019
1488	31/07/2019
1489	03/10/2019
1490	31/07/2019
1491	03/10/2019
1492	31/07/2019
1493	29/08/2019
1495	09/09/2019
1496	16/09/2019
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Appendix 2 Full list of individual fingerprints collected from Thiel-embalmed bodies

Can be found in an electronic format on a compact disc (shared folder) included as a supplementary material to the thesis.

Appendix 3 Fingerprints selected for the analysis by fingerprint examiners

Can be found in an electronic format on the compact disc (shared folder) included as supplementary material to the thesis.

Contains 80 scanned fingerprints collected using black powder, and 80 original images representing fingerprints collected using post-powder photography.

Appendix 4 Ethical approval and amendments

School of Science
and Engineering
University of Dundee

Centre for Anatomy and Human Identification

Dr Caroline Erolin
T: 01382 388352
e: c.d.erolin@dundee.ac.uk
19/04/2018

CAHIDEC76 – *Understanding the relationship between epidermal and dermal fingerprints*

Dear Veronika,

On behalf of the School of Science and Engineering ethics committee I am pleased to provide ethical approval for the project titled 'Understanding the relationship between epidermal and dermal fingerprints'.

This approval is granted until 02/10/2020 Please note that you should update the ethics committee should any of the circumstances of the project change.

Kindest regards

Caroline Erolin

Dr Caroline Erolin

Senior Lecturer
Centre for Anatomy and Human Identification
University of Dundee

SREC Post-Approval Request for Amendment Decision Letter Template
Version 1, 14th January 2019

University of Dundee

School of Science and Engineering SREC

University of Dundee
Dundee
DD1 4HN

22/03/2019

Dear Veronika,

Original Application Number: CAHIDEC76

Title of Project: Understanding the relationship between epidermal and dermal fingerprints

I am writing to advise you that your post-approval request for an amendment to your previously approved ethics application has been reviewed and approved on behalf of the School of Science and Engineering SREC.

Approval is valid for the duration of the project, as stated in the original application. Should you wish your study to continue beyond the stated project end date, you must request an extension to this approval using the Post-Approval Request for an Extension form. The extension request must be lodged during your period of study and the period requested must not extend beyond the deadline for submission of your research project.

Yours sincerely

Dr Caroline Erolin
Convener, School of Science and Engineering

School of Science
and Engineering
University of Dundee

Centre for Anatomy and Human Identification

Dr Catriona Davies
T: 01382 384220
e: c.m.davies@dundee.ac.uk
30/10/2019

CAHIDEC76 – Understanding the relationship between epidermal and dermal fingerprints

Dear Veronika

On behalf of the School of Science and Engineering ethics committee I am pleased to provide ethical approval for the project titled 'Understanding the relationship between epidermal and dermal fingerprints'.

This approval is granted until 2nd October 2020. Please note that you should update the ethics committee should any of the circumstances of the project change.

Kindest regards

Dr Catriona Davies

Lecturer
Centre for Anatomy and Human Identification
University of Dundee

Appendix 5 Letter (email) to potential participants

Dear potential participant,

I am a PhD student at the University of Dundee researching the relationship of epidermal and dermal fingerprints from Thiel-embalmed cadavers. I would like to invite you to participation in my inter-observer study.

I am looking for forensic examiners with experience in fingerprint analysis. This study will involve comparison between pairs of dermal and epidermal fingerprints collected using black powder and photography. I will also ask you to record the quality of given fingerprints, the range of minutiae characteristics found on each fingerprint, the range of matching minutiae characteristics, and whether or not the pairs compared would result in an identification (positive ID, negative ID, unable to exclude, insufficient).

I have attached a copy of participant information sheet with more details of the study, as well as the participant consent form. Please read through the documents and, if you would like to participate in this inter-observer study, contact me via telephone or email provided below.

Your potential interest and help is greatly appreciated.

Kind regards,

Veronika Dzetkulicova

Veronika Dzetkulicova, MSc.

PhD student and Anatomy and Forensic Anthropology Demonstrator

Centre for Anatomy and Human Identification

University of Dundee

MSI/WTB/JBC Complex

Dow Street, Dundee

DD1 5EH

Tel: +44 (0) 1382384210

Email: v.dzetkulicova@dundee.ac.uk

Appendix 6 Participant information sheet

University of Dundee

PARTICIPANT INFORMATION SHEET

Version 2.0 13.06.2017

Project title: Understanding the relationship between epidermal and dermal fingerprints

Investigators: Veronika Dzetkulicova (student), Dr Lucina Hackman (supervisor), Dr Helen Langstaff (supervisor)

Invitation:
You are being asked to take part in a research study. Before you decide if you would like to take part, it is important you understand why the research is being done and what it involves. Please take your time to read the following information carefully and feel free to ask any questions. If you agree to take part in the study, you will be asked to sign a consent form. Thank you for your time.

Purpose of the research:
This study is being undertaken by Veronika Dzetkulicova as part of the PhD in Anatomy and Forensic Anthropology at the University of Dundee.

We wish to undertake some research work which involves comparison of epidermal and dermal fingerprints taken from individuals bequeathed to the Centre of Anatomy and Human Identification. The fingerprints were collected using black powder and photography. The aim of the study is to quantify similarities and differences in epidermal/dermal fingerprint characteristics and to assess the standard of the print recovered.

Procedures:
You will be asked to compare 40 potential pairs of fingerprints which were collected using black powder and 40 potential pairs of fingerprints that were collected using photography. You will be asked to record the quality of each given fingerprint. You will be asked to establish and record following ID statuses for each pair: 'positive', 'negative', 'unable to exclude', and 'insufficient'. You will also be asked to record a range of minutiae characteristics found for each investigated fingerprints as well as a range of matching minutiae characteristics for each pair. The time required for this task will depend on the quality of each fingerprint pair and may vary between 10 to 45 minutes per pair.

Participation:
It is up to you to decide if you would like to take part. Your participation is voluntary and you are free to withdraw from the study at any time.

Risks:
There are no physical or emotional risks connected to the tasks you are asked to participate in.

Cost, reimbursement and compensation:
You will not receive any payment (or equivalent) for your participation in this project.

Confidentiality
The data collected will not contain any personal information about you.

It will not be possible to link publicly the data you provided to your identity and name.

All digital data and documents containing (or linking to) the original identification of the participants will be stored securely on an encrypted hard-drive and locked securely by Dr Lucina Hackman, only accessible to the named researchers.

The specific data recorded will only be accessible to the named researchers and will be stored for a period of no less than 10 years, after which time the files will be destroyed.

The anonymised results of the study may be used in future publications and incorporated into databases to inform future professional practice.

Further information
Veronika Dzetkulicova, Dr Lucina Hackman and Dr Helen Langstaff will be glad to answer your questions about this study at any time. If you want to find out about the final results of this study, you may contact them at:

v.dzetkulicova@dundee.ac.uk
l.hackman@dundee.ac.uk
h.langstaff@dundee.ac.uk

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Dr Caroline Erolin
Centre for Anatomy and Human Identification
Chair Ethics Committee
University of Dundee
Dow Street
Dundee
DD1 5EH

Telephone: +44(0)1382 38 8352/8627
Email: c.d.erolin@dundee.ac.uk

Appendix 7 Participant consent form

University of Dundee

University of Dundee

Version 1.1 25.06.2017

Understanding the relationship between epidermal and dermal fingerprints

INTEROBSERVER PARTICIPANT CONSENT FORM

- The research project and the procedures have been explained to me.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, without having to give a reason and without any consequences to my professional standing or employment.
- I understand my role in this project and the methods that I am to follow to collect data.
- I consent to undertaking interobserver data collection for this project.

_____ _____

Participant's signature Date

_____

Participant's name

Appendix 8 Examples of epidermal-dermal fingerprint pairs analysed by fingerprint examiners

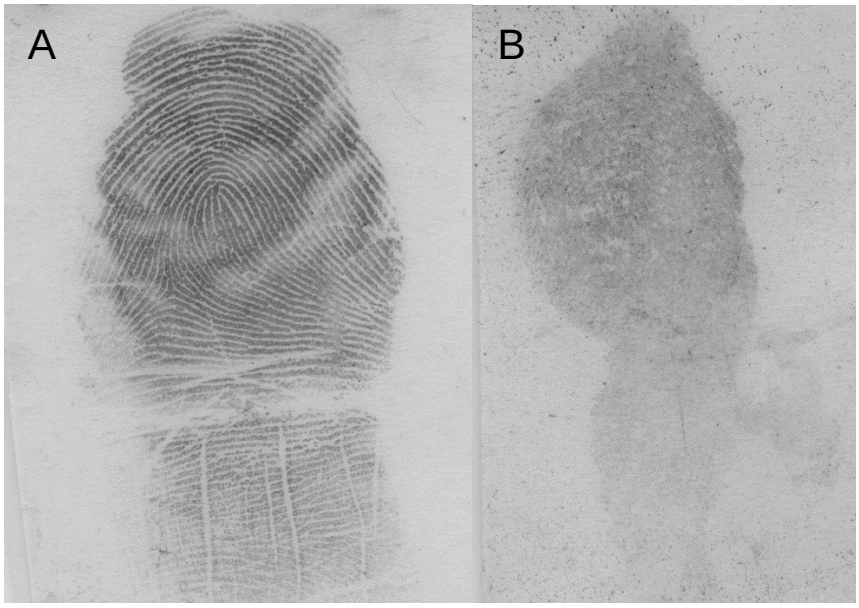

Figure 4.4.1 Appendix 8 - Photograph of epidermal (A) and dermal (B) fingerprints collected using powder.

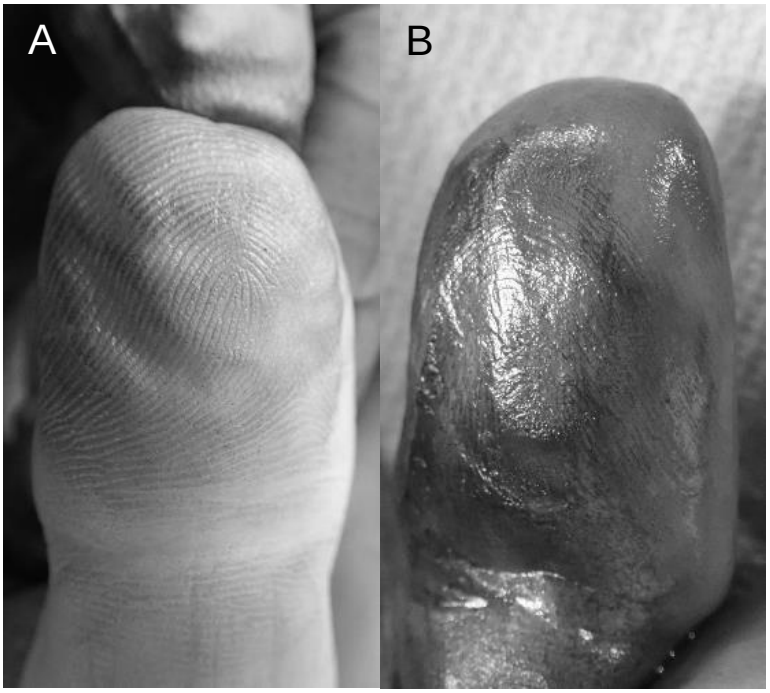

Figure 4.4.2 Appendix 8 - Photograph of friction ridge epidermis (A) and dermis (B).

Appendix 9 Expert data recording sheet example

INTER-OBSERVER NUMBER							
Years of experience (optional)							
POWDER PHOTOGRAPHY							
pair number	A quality grade	B quality grade	A minutiae	B minutiae	Match minutiae	ID outcome	Notes
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

LEGEND

Quality: 1 = insufficient, 2 = suitable for manual comparison, 3 = suitable for IDENT1 comparison
Minutiae numbers: 0, low (< 10), medium (10 to 20), high (>20)
ID outcome: positive, negative, insufficient, unable to exclude

INTER-OBSERVER NUMBER							
Years of experience (optional)							
POWDER PHOTOGRAPHY							
pair number	A quality grade	B quality grade	A minutiae	B minutiae	Match minutiae	ID outcome	Notes
21							
22							
23							
24							
25							
26							
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28							
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31							
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34							
35							
36							
37							
38							
39							
40							

LEGEND

Quality: 1 = insufficient, 2 = suitable for manual comparison, 3 = suitable for IDENT1 comparison
Minutiae numbers: 0, low (< 10), medium (10 to 20), high (>20)
ID outcome: positive, negative, insufficient, unable to exclude

Appendix 10 R script and raw data for statistical analysis of Krippendorff alpha coefficients and their confidence intervals

Can be found in an electronic format on a compact disc (shared folder) included as a supplementary material to the thesis.

Appendix 11 Manuscript – Histology of epidermal desquamation

As it appeared upon submission to the Annals of Anatomy. Due to rejection received from Annals of Anatomy, the manuscript will be adjusted and submitted for consideration to a more forensic science-oriented journal.

Annals of Anatomy

Epidermal desquamation in Thiel-embalmed cadavers: a histological study

--Manuscript Draft--

Manuscript Number:	AANAT3498
Article Type:	Research Article
Keywords:	Thiel embalming; epidermal desquamation; skin histology.
Corresponding Author:	Veronika Dzetkuličová, M.Sc. University of Dundee Dundee, Angus UNITED KINGDOM
First Author:	Veronika Dzetkuličová, M.Sc.
Order of Authors:	Veronika Dzetkuličová, M.Sc.
	Helen Langstaff
	Lucina Hackman
Abstract:	Background: Epidermal desquamation occurs during the fixation of a body using Thiel embalming fluid. The current literature is vague on the histology of the desquamated skin layer in Thiel-embalmed bodies and the timeframe within which this desquamation ensues. If the desquamation occurs between the epidermis and dermis it provides an opportunity to study the relationship between the epidermal and dermal dermatoglyphics of Thiel-embalmed bodies. The aim of the study is to describe the histology of epidermal desquamation that occurs during the first six weeks of the Thiel embalming process.Methods: Skin of the thumb from the left hand of cadavers (N = 40) was sampled using a standard skin biopsy punch. Twenty bodies were sampled prior to embalming and then in weekly intervals for up to six weeks after the immersion in the embalming fluid. A further twenty bodies were sampled after the completion of embalming but no sample was collected prior to embalming. The skin biopsy was fixed in formalin, dehydrated in ascending concentrations of ethanol, and paraffin-embedded. Microtome skin sections were stained with haematoxylin and eosin and visualised using optical light microscopy.Results and Conclusions: During the 6 week period partial and complete epidermal desquamation was observed at two levels of the thick skin – within or below the stratum lucidum (SL) and at the epidermal-dermal junction (EDJ). Complete epidermal desquamation at the EDJ level was observed in 10 out of 20 histological sections sampled after one week of immersion in Thiel-embalming fluid. Complete epidermal desquamation at the EDJ level was observed in 17 out of 20 histological sections sampled after four weeks of immersion in Thiel-embalming fluid. Complete epidermal desquamation at the EDJ was observed in all 20 histological sections sampled after the completion of embalming.
Suggested Reviewers:	Noel T Boaz Professor of Anatomy, Emory and Henry College nboaz@ehc.edu The only histological image of epidermal desquamation from Thiel-embalmed bodies was found in his presentation published online.
	Ingrid Kerckaert Universiteit Gent Ingrid.Kerckaert@UGent.be Published on using Thiel-embalmed bodies in clinical setting.

Cover Letter

Dundee, 12th November 2019

Dear Editors,

I would like to submit a manuscript titled "*Epidermal desquamation in Thiel-embalmed cadavers: a histological study*" to the Annals of Anatomy. The manuscript describes histology of previously un-studied epidermal desquamation in Thiel-embalmed cadavers. This paper contributes to an understating of histological skin changes occurring in bodies preserved by the Thiel embalming technique. The outcomes of the study also uncovered further potential uses of Thiel-embalmed cadaveric material outside of the clinical anatomy area. I hope the selected topic fits your journal and look forward to receiving your decision.

Sincerely,

Veronika Dzetkuličová

Conflict of Interest

Declaration of Interest

None.

Epidermal desquamation in Thiel-embalmed cadavers: a histological study

Authors and Affiliations:

Veronika Dzetkulicova[1] (v.dzetkulicova@dundee.ac.uk), Helen Langstaff[2] (h.langstaff@dundee.ac.uk), Lucina Hackman[1] (l.hackman@dundee.ac.uk)

[1]Leverhulme Research Centre for Forensic Science, University of Dundee, Small's Lane, DD1 4HN United Kingdom.

[2]Centre for Anatomy and Human Identification, University of Dundee, Dow Street DD1 5EH, Dundee, United Kingdom.

Corresponding Author:

Veronika Dzetkulicova, v.dzetkulicova@dundee.ac.uk

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Abstract

Background: Epidermal desquamation occurs during the fixation of a body using Thiel embalming fluid. The current literature is vague on the histology of the desquamated skin layer in Thiel-embalmed bodies and the timeframe within which this desquamation ensues. If the desquamation occurs between the epidermis and dermis it provides an opportunity to study the relationship between the epidermal and dermal dermatoglyphics of Thiel-embalmed bodies. The aim of the study is to describe the histology of epidermal desquamation that occurs during the first six weeks of the Thiel embalming process.

Methods: Skin of the thumb from the left hand of cadavers (N = 40) was sampled using a standard skin biopsy punch. Twenty bodies were sampled prior to embalming and then in weekly intervals for up to six weeks after the immersion in the embalming fluid. A further twenty bodies were sampled after the completion of embalming but no sample was collected prior to embalming. The skin biopsy was fixed in formalin, dehydrated in ascending concentrations of ethanol, and paraffin-embedded. Microtome skin sections were stained with haematoxylin and eosin and visualised using optical light microscopy.

Results and Conclusions: During the 6 week period partial and complete epidermal desquamation was observed at two levels of the thick skin – within or below the *stratum lucidum* (SL)[1] and at the epidermal-dermal junction (EDJ)[2]. Complete epidermal desquamation at the EDJ level was observed in 10 out of 20 histological sections sampled after one week of immersion in Thiel-embalming fluid. Complete epidermal desquamation at the EDJ level was observed in 17 out of 20 histological sections sampled after four weeks of immersion in Thiel-embalming fluid. Complete epidermal desquamation at the EDJ was observed in all 20 histological sections sampled after the completion of embalming.

Key words: Thiel embalming, epidermal desquamation, skin histology

1 Introduction

The Thiel embalming method, developed by the anatomist Walter Thiel, preserves bodies by intravascular perfusion and subsequent immersion in Thiel embalming solution (Thiel, 1992). The original embalming solution developed by Walter Thiel contains fixatives

[1] SL – *stratum lucidum*
[2] EDJ – epidermal-dermal junction

(ammonium and potassium nitrates, 4-chloro-3-methylphenol, formaldehyde), disinfectant (boric acid) and plasticity preservative (ethylene glycol) (Thiel, 1992). This original embalming solution recipe has been made openly available and has been adjusted by various institutions since it was first developed. Ottone et al. (2016) offer a review of adjustments made to the original formula and the embalming procedure made by these various institutions across the world. Modifications range from simplification of perfusion (Hammer et al., 2015) to preservation in tropical environments (Reddy et al., 2017), and enhanced preservation of brain tissues (Thiel, 2002). The department of Anatomy at the University of Dundee adjusted the original Thiel formula to lower the concentration of formalin used during embalming (Eisma et al., 2013). The subsequent reduction in exposure to noxious irritating gases is one of the advantages of using Thiel embalming fluids over the more wide-spread use of the formalin embalming method (Balta et al., 2015; Rocha Ferreira et al., 2017). The other main advantages of Thiel embalming include; retained flexibility of muscles and passive mobility in joints (Benkhadra et al., 2012), preservation of tissue colours and plasticity (Hunter et al., 2014), and the option to retain vascular repletion (Odobescu et al., 2014) whilst allowing for storage at room temperature for a duration of years (Eisma and Wilkinson, 2014). Within the University of Dundee, Thiel-embalmed bodies are used for teaching and training of students (medicine, dentistry, anatomy, anthropology, medical art) and professionals practicing various surgical and micro-surgical procedures (Eisma and Wilkinson, 2014; Healy et al., 2015; László et al., 2018; Lone et al., 2017; Wolff et al., 2008).

The detachment of the epidermal layer (epidermal desquamation) is a known 'by-product' of Thiel embalming (Eisma et al., 2013; Kerckaert et al., 2008; Kocbek and Rakusa, 2017; Thiel, 1992). Some authors also mention the formation of bullae, blister-like detachment of the epidermis from the dermis, creating a space filled with fluid (Boaz, n.d.; Kerckaert et al., 2008). However, minimal specific attention is given to Thiel-embalming-induced epidermal desquamation in the literature. Only Boaz (n.d.) provides histological section evidence of a layer of skin detaching during Thiel embalming process. He describes superficial epidermal desquamation occurring between the *stratum corneum* and *stratum malpighii,* yet by claiming the bullae are formed during Thiel embalming he also indirectly points towards the detachment of the epidermis from dermis. Additionally, Boaz (n.d.) provides no description of the sample size or time of skin sampling when making the

histological sections. Thiel (1992) and Eisma et al. (2013) do not mention skin histology in connection to Thiel-embalming-induced epidermal desquamation simply stating that the epidermal layer detaches. Likewise, Kerckaert et al. (2008) and Kocbek and Rakusa (2017) only mention the occurrence of desquamation of the epidermis in Thiel-embalmed bodies which indirectly suggests that there is a detachment of the epidermis from dermis. Similarly, there is a lack of controlled specific studies about the timeframe of Thiel-embalming-induced epidermal desquamation. The interval between the embalming and the occurrence of desquamation is reported to vary starting from the first days after embalming, depending on the body part and amount of body handling (Eisma et al., 2013).

The aim of the study was to describe various types of epidermal desquamation observed in histological thick skin sections sampled at various timeframes during Thiel-embalming process. If the desquamation occurs between the epidermal and dermal layer, the exposure of the dermal layer allows for yet another application of Thiel-embalmed bodies – fingerprint research. The opportunity to collect and compare dermal fingerprints directly to their epidermal counterparts has a research and training potential in areas such as fingerprint collection from deceased individuals and disaster victim identification (Mizokami et al., 2015; Morgan et al., 2006; Okajima, 1984).

2 Materials and Methods

2.1.1 Sample

A sample of skin was taken from the left thumb of deceased individuals who presented with no apparent disruption of the skin or visible skin pathology. No medical information besides the cause of death was available for the sampled individuals; therefore, it was not possible to confirm/refute any potential skin pathology not visible to the naked eye. A standard biopsy skin punch (Ø = 4 mm) was inserted into the centre of skin on the palmar surface of the distal left thumb (Figure 1). The tissue column was carefully taken out (where necessary with the use of forceps) and placed into a plastic container with a lid.

[insert Figure 1]

Samples were taken from 40 bodies bequeathed to the Centre for Anatomy and Human Identification at the University of Dundee (Table 1 and 2). All procedures performed

in the study were in accordance with the ethical standards of the institutional research committee and in accordance with Scottish legislation (the Anatomy Act 1984 and the Human Tissue (Scotland) Act 2006). The population used in the current study was of European white origin. Only one sample was taken from bodies 1-20 (see Table 1); these samples were taken after the body had been embalmed and had between 162 and 258 days of immersion in Theil embalming fluid. The samples were analysed as post-embalming controls. For bodies numbered 21-40 (see Table 2), samples were taken prior to immersion of the body in the Thiel embalming fluid and then at weekly intervals for between four and six weeks after immersion had occurred, allowing the study of the effect of time on epidermal desquamation caused by immersion in the Thiel embalming fluid. A four-week interval was selected initially (N = 8). The time was extended to a six-week interval (N = 12) after it became evident that complete epidermal desquamation was not occurring for all bodies after four weeks.

[insert Table 1 and 2]

2.1.2 Histological processing

All the protocols applied on histological sample processing have been previously used in the histological analysis of Thiel-embalmed muscle tissue (Tennent 2014). The same protocols were also applied to the samples taken prior to embalming to ensure comparability across the samples.

Immediately after the collection, each sample was immersed in 10 ml of 10% neutral-buffered formalin and left overnight. The samples were dehydrated by step-wise immersion into ethanol solutions with ascending concentrations according to the following protocol:

50% ethanol 1 h
70% ethanol 1 h
80% ethanol 1 h
90% ethanol 1 h
100% ethanol 1 h
100% ethanol 1 h
100% ethanol overnight

The samples were then transferred into individual glass vials, cleared (10 ml of xylene, mixture of isomers), and immersed in paraffin (molten, 60°C in oven) following this protocol:

xylene	1 h
xylene	2 h
paraffin	1 h
paraffin	2 h
paraffin	2 h

The samples were then embedded in fresh paraffin and sectioned using a microtome (Leica, Jung RM2035) with 5 µm thickness of slices. The samples were sectioned until the samples' maximum width (biopsy punch Ø = 4 mm) was exposed. The slices were placed on microscopic slides using a water bath (t = 50°C), air-dried and then incubated in the oven at 60°C for 2 hours.

The microscopic slides (cooled down to room temperature) with adhered samples were stained with haematoxylin and eosin using the following protocol (slide holder containing maximum of 12 slides was transferred to and from approximately 200 ml of each of the listed solutions):

Histoclear	3 min
Histoclear	3 min
100% ethanol	3 min
100% ethanol	3 min
70% ethanol	3 min
tap water	3 min
Mayer haematoxylin	3 min
tap water	3 min
Scott's tap water	30 sec
tap water	2 min
eosin	5 min
tap water	10 sec
95% ethanol	15 sec
100% ethanol	2 min
100% ethanol	2 min

100% ethanol	2 min
xylene	3 min
xylene	3 min

The slides were then mounted with DPX mounting medium, cover-slipped and left to dry in a fume hood overnight.

2.1.3 Histological slide observation and definitions of epidermal desquamation

Each histological slide was observed by one observer using optical light microscopy (Leica DM2000) under the magnification of × 400. Images of histological sections were acquired using a camera (Leica DFC 295) coupled with the microscope. The skin layers were observed along the full width of the histological sections. All types of epidermal desquamation that were observed were recorded. Partial epidermal desquamation at the level of *stratum lucidum* (SL) was defined as a detachment of more than one cell from other cells within the *stratum lucidum* or *stratum granulosum* (Figure 2). Partial epidermal desquamation at the level of epidermal-dermal junction (EDJ) was defined as a detachment between the epidermal cells of *stratum basale* and dermal papillae observed at more than one dermal papilla (Figure 2). If the cellular detachment spanned the approximate length of one cell from sublayer below, it was not recorded as partial desquamation (Figure 3A). If the cellular detachment was observed solely at the very ends of the histological section, it was not recorded as partial desquamation due to the possibility of it being caused by mechanical sample manipulation during biopsy excision or embedding (Figure 3B). Complete epidermal desquamation at the level of SL was defined as a complete detachment of *stratum corneum* together with *stratum lucidum* from the *stratum granulosum* of given histological section (Figure 4A). Complete epidermal desquamation at the level of EDJ was defined as a complete detachment of the epidermis from the dermis (Figure 4B).

[insert Figures 2 – 4]

3 Results

3.1.1 Post-embalming controls

Complete epidermal desquamation at the level of epidermal-dermal junction was observed in all 20 histological sections sampled from bodies after completion of the Thiel embalming process. The dermis was exposed in all the histological sections with observable

dermal papillae. No epidermis was observed in any of the histological sections taken from fully embalmed individuals hence no observations of *stratum lucidum* and the desquamation process could be made.

3.1.2 Temporal study samples

Figure 5 and 6 contain observed types of epidermal desquamation in the 20 bodies sampled prior to embalming and then weekly for four and six weeks after the embalming.

[insert Figure 5 and 6]

Both partial and complete epidermal desquamation was observed at the level of *stratum lucidum* SL during the four- and six-week observations. Partial epidermal desquamation at this level was observed in histological sections sampled prior to embalming (19 out of 20 bodies), as shown in pre-embalming column of Figure 5 and 6. The number of histological sections with partial epidermal desquamation at the SL skin level decreased after initial immersion in embalming fluid. Complete epidermal desquamation at the SL skin level was observed in five histological sections (Figure 5, ID 27, 38, and 39). Complete epidermal desquamation at the SL skin level was observed in histological sections sampled after three, four and five weeks of the immersion in embalming fluid. Complete lack of any evidence for epidermal desquamation at the SL level was observed in up to four histological sections from each week of sampling.

Both types of epidermal desquamation were observed at the EDJ level during the four- and six-week observations. Partial epidermal desquamation at the EDJ level was most prevalently observed in histological sections sampled prior to embalming (15 out of 20 bodies, Figure 5). The number of histological sections with observed partial epidermal desquamation at this skin level decreased after the immersion in embalming fluid. Complete epidermal desquamation at the EDJ level was observed in half of the histological sections sampled after one week of immersion in embalming fluid (10 out of 20, Figure 5). Complete epidermal desquamation at the EDJ level was observed in the highest number (17 out of 20) of histological sections sampled after four weeks of immersion in embalming tank (Figure 5). There were two bodies without complete epidermal desquamation at the EDJ level in any of the histological sections (Figure 6; ID 26 and 30). No epidermal desquamation at the level of EDJ was observed in five histological sections sampled prior to embalming (Figure 6; ID 21,

26, 27, 34, and 39) and one histological section sampled after five weeks of immersion in embalming fluid (Figure 6; ID 26).

4 Discussion

Our results demonstrate that epidermal desquamation in Thiel-embalmed bodies was observed at two levels of the thick skin – within or below the *stratum lucidum* and at the epidermal-dermal junction. Two types of epidermal desquamation (partial or complete) were observed in histological sections at both skin levels at some point prior, during, and after Thiel embalming. Complete epidermal desquamation at the EDJ was observed in all 20 histological sections sampled after the completion of embalming. Partial epidermal desquamation at both skin levels was the most prevalently observed in histological sections sampled prior to embalming (19 out of 20 histological sections at the SL skin level, 15 out of 20 histological sections at the EDJ level). Complete epidermal desquamation was not observed in pre-embalming samples at any of the skin layers. Complete epidermal desquamation at the SL skin level was observed in five histological sections exposed to Thiel embalming fluid. Complete epidermal desquamation at the EDJ level was observed in 10 out of 20 histological sections sampled after one week of immersion in Thiel-embalming fluid and in 17 out of 20 histological sections sampled after four weeks of immersion in Thiel-embalming fluid.

Partial epidermal desquamation at the SL level occurred in pre-embalming samples. Partial epidermal desquamation within the *stratum corneum* and *stratum lucidum* was also observed in images of normal human thin and thick skin sections (Gudjonsson et al., 2007; Kerr, 2010; Khavkin and Ellis, 2011; Ross and Pawlina, 2016). The literature suggests partial desquamation at this skin level prior to embalming is a part of natural desquamation process. Moreover, the advanced age at death of sampled individuals could have an effect on the extent of partial epidermal desquamation at the SL level observed in pre-embalming samples. Desmosomes are larger in dry skin of elderly people, the turnover of keratinized cells is reduced and the keratinized epidermal layer is thicker, meaning superficial epidermal desquamation of the topmost skin layer is reduced (Hara, 1993). However, the lamellar lipid envelope between the *stratum lucidum* and *stratum granulosum* is disorganised and changes structure in dry aged skin compromising its stability and water non-permeability (Elias, 1983; Rawlings, 2017). The structurally-changed lipid layer between the *stratum*

lucidum and *stratum granulosum* occurring in dry aged skin could be an explanation of observed partial epidermal desquamation in the pre-embalmed histological sections of the current study.

In some histological sections, no epidermal desquamation at the SL skin level was observed after immersion in Thiel embalming fluid, despite partial epidermal desquamation in the pre-embalming histological section taken from the same individuals. This adherence within the SL skin layer after the exposure to Thiel embalming fluid could be an effect of the fixative chemical components within the embalming solution. However, the exact biochemical processes and chemical components involved in possible adherence of the skin layers remain to be investigated, as research has focused only on the biochemical effects of Thiel on muscular proteins and collagen (Benkhadra et al., 2012; Tennent, 2014). It is also important to mention that the number of histological sections containing epidermal layers was reduced by the increasing occurrence of complete epidermal desquamation at the EDJ (macroscopic loss of epidermis prior to sampling). Therefore, adherence within the keratinized layers of epidermis after the immersion in Thiel embalming fluid was not observable in all histological samples. Likewise, the extent of partial epidermal desquamation at the SL layer could not be assessed in all histological sections.

Complete epidermal desquamation at the SL skin level was observed in five histological sections (present in three bodies out of 20). This type of epidermal desquamation was coupled with partial epidermal desquamation at the EDJ in cases of three histological sections (two bodies, ID numbers 27 and 38). Such complete epidermal desquamation at SL in Thiel-embalmed bodies was observed by Boaz (n.d.) who did not state the number of cases in which such desquamation was observed, nor did he state whether there was any epidermal desquamation observed at the EDJ. In two histological sections (ID numbers 27 and 39), complete epidermal desquamation at the SL level coupled with complete epidermal desquamation at the EDJ was observed. Although the prevalence of complete epidermal desquamation at the SL skin level appears to be low, it is impossible to state the exact number of cases with such epidermal desquamation due to macroscopic loss of the epidermis prior to sampling took place (associated with complete desquamation at the EDJ).

Partial epidermal desquamation was observed at the EDJ skin level in 15 out of 20 histological sections prior to Thiel embalming; the rest of the histological sections showed

no epidermal desquamation at this skin layer. Clark et al. (2006) claim that loosening of the epidermis from the dermis can be visible form up to 48 hours after death. Clark et al. (2006) call this process skin slippage and explain the separation of the skin layers as a release of hydrolytic enzymes by cells at the epidermis-dermis junction. There was an interval of one to five days between death of the individuals and their embalming. Based on observations of Clark et al. (2006), the individuals with no observed partial epidermal desquamation at the EDJ would be expected to have an interval between death and embalming which is shorter than two days. However, histological sections in which no epidermal desquamation at the EDJ was observed came from individuals with one, three, or four-day intervals between death and embalming. Other factors such as environmental and individual differences could influence epidermal desquamation at the EDJ skin level prior to embalming. Temperature is an example of environmental factors affecting the performance of autolytic enzymes during body decomposition (Gill-King, 2006); the enzymes decrease their activity with decreasing temperature with concomitant body decomposition rate decreases. Therefore, in cases of bodies being stored in fridge or freezer for the interval between death and embalming, the autolysis of EDJ could be hampered. Unfortunately, no information about the storage (fridge or freezer, time of the storage) of the bodies for the interval between death and embalming was available to us. Furthermore, individual's pathologies, occupation, and age influence the structure and function of EDJ and could have an effect on partial epidermal desquamation prior to embalming (Langton et al., 2016; Montagna and Carlisle, 1979).

Complete epidermal desquamation at the EDJ was observed in at least one histological section sampled from 38 (out of 40) Thiel-embalmed bodies. Complete epidermal desquamation at this skin level was observed in all 20 histological sections sampled from fully-embalmed bodies. There is no literature to date explaining which chemical from Thiel embalming solution could cause the detachment of epidermal-dermal junction on microscopic level. However, on a macroscopic level there is mechanical manipulation when handling the embalming or embalmed bodies causing potential detachment of skin layers (Eisma et al., 2013). Prior to embalming the bodies are manually ‘scrubbed’ (the loosened epidermis is manually detached and removed if still attached to the body) as a part of the body preparation process after the body is taken out of tank (i.e. fully embalmed) and sealed in plastic bag. The body preparation process therefore

contributes to the observed complete epidermal desquamation in all fully embalmed bodies.

The timeframe of complete epidermal desquamation at the EDJ in Thiel-embalmed bodies varies. This type of epidermal desquamation was observed in half of the histological sections sampled during the first week of immersion in Thiel embalming fluid. However, complete epidermal desquamation at the EDJ was not observed in two bodies sampled for the duration of first four and six weeks of immersion in Thiel embalming fluid (ID numbers 30 and 26, respectively). As previously mentioned, thinning, straightening of EDJ and subsequent skin fragility are the result of aged skin undergoing intrinsic biochemical changes as well as changes due to extrinsic factors (photo-ageing, manual work) (Khavkin and Ellis, 2011; Langton et al., 2016; Montagna and Carlisle, 1979). The amount of generic shearing forces and friction applied to the thick skin on thumbs combined with the old age of bequeathed individuals will most likely have an effect on the timeframe of complete epidermal desquamation at the EDJ. However, this claim is unsupported by data, as no information about occupation of bequeathed individuals is available. Lastly, the quality of hand vascular structures could have an effect on timeframe of Thiel-induced epidermal desquamation at the EDJ. The initial perfusion of a body by Thiel embalming fluid is dependent on the state of veins and arteries (Ottone et al., 2016). If the vasculature of hands is poor, perfusion fluid might not reach the hands and digits properly, interfering with the quality of embalming in the hands (Eisma et al., 2013; Kerckaert et al., 2008; Kocbek and Rakusa, 2017). Drying of the tissues in hands could subsequently have an effect on epidermal desquamation at any skin level. However, larger sample size will be needed to confirm the trends observed in epidermal desquamation in Thiel-embalmed bodies.

5 Conclusion

Epidermal desquamation was observed in thick skin histological sections sampled from Thiel-embalmed bodies at two levels: *stratum lucidum* and epidermal-dermal junction. We observed two types of epidermal desquamation, partial and complete, at the two skin levels. Partial epidermal desquamation was observed at both skin levels in most histological sections sampled prior to embalming. Complete epidermal desquamation at the EDJ was observed more frequently than complete epidermal desquamation at the SL skin level in histological sections sampled from Thiel-immersed bodies. We observed individual variation

in timeframe of epidermal desquamation at the EDJ level, but complete epidermal desquamation at the EDJ was observed in half of the histological sections sampled after the first week of immersion in Thiel embalming fluid. Since complete epidermal desquamation at the EDJ exposed the dermis in thick friction ridge skin, the Thiel-embalmed bodies could be used for the study of dermatoglyphics in dermal fingerprints.

Author Contributions

Veronika Dzetkulicova: Conceptualisation, Data curation, Formal Analysis, Investigation, Visualisation, Writing – original draft.

Helen Langstaff: Conceptualisation, Supervision, Writing – review and editing.

Lucina Hackman: Conceptualisation, Supervision, Writing – review and editing.

Declaration of Interest

None.

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Tables

Table 1. Details about bequeathed individuals sampled as post-embalming controls.

Individual number	***Sex (M = male, F = female)***	***Age at death***	***Total number of days in embalming tank***
1	F	71	199
2	F	84	202
3	M	88	175
4	F	70	258
5	F	67	226
6	M	83	205
7	F	103	184
8	M	90	176
9	M	78	217
10	M	49	177
11	M	61	175
12	M	94	201
13	F	88	197
14	F	56	186
15	M	63	186
16	M	73	178
17	M	91	163
18	M	71	162
19	F	92	162
20	M	83	190
Mean	-	77.03	181.85

Table 2. Details about bequeathed individuals sampled for temporal study on the effect of Thiel embalming fluid on epidermal desquamation.

Individual number	*Sex (M = male, F = female)*	*Age at death*	*Days between death and embalming*	*Total number of samples taken per body*
21	M	98	1	5
22	F	91	2	5
23	F	90	3	5
24	F	84	4	5
25	F	75	3	5
26	F	81	4	7
27	F	77	1	7
28	M	62	5	5
29	F	96	1	5
30	F	90	2	5
31	F	74	3	7
32	M	74	2	7
33	F	86	3	7
34	F	97	3	7
35	M	62	2	7
36	F	80	3	7
37	F	92	1	7
38	M	79	3	7
39	M	63	4	7
40	M	86	2	7
Mean	-	81.85	2.6	6.2

Figure Legends

Figure 1. Standard biopsy skin punch inserted into the skin of distal left thumb. White arrow shows direction of subsequent sampling.

Figure 2. Histological sections of skin sample, stained with haematoxylin and eosin; solid line = epidermis, dashed line = dermis, * = examples of dermal papillae. Partial epidermal desquamation at the level of *stratum lucidum* (SL) (solid black arrows) and partial epidermal desquamation at the level of epidermal-dermal junction (EDJ) between *stratum basale* and dermis (black dashed arrows).

Figure 3. Histological sections of skin sample stained with haematoxylin and eosin. (A) Cellular detachment within epidermal layer (approximately along one cell length) not counted as desquamation at the level of *stratum lucidum* (black arrow). (B) Mechanical

separation of epidermal layers at the end of the histological section (black arrow) not counted as desquamation at the level of *stratum lucidum*.

Figure 4. Histological sections of skin sample stained with haematoxylin and eosin, solid line = epidermis, dashed line = dermis, * = examples of dermal papillae. (A) Complete epidermal desquamation at the level of *stratum lucidum* (solid black arrows). (B) Complete epidermal desquamation at the level of epidermal-dermal junction (dashed black arrows).

Figure 5. Types of epidermal desquamation observed in histological sections during different phases of Thiel embalming. SL = epidermal desquamation observed at *stratum lucidum*, EDJ = epidermal desquamation observed at epidermal-dermal junction.

Figure 6. Types of epidermal desquamation observed in histological sections from individual bodies during different phases of Thiel embalming; SL = skin level of *stratum lucidum*, EDJ = skin level of epidermal-dermal junction, PRE-E = pre-embalming, WK1-6 = week 1-6 of immersion in embalming tank.

Figure 1

Click here to download Figure Figure 1.tif

Figure 2

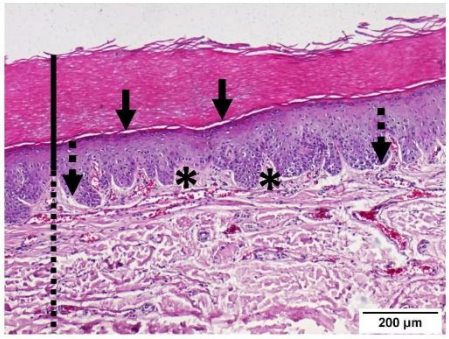


Figure 3

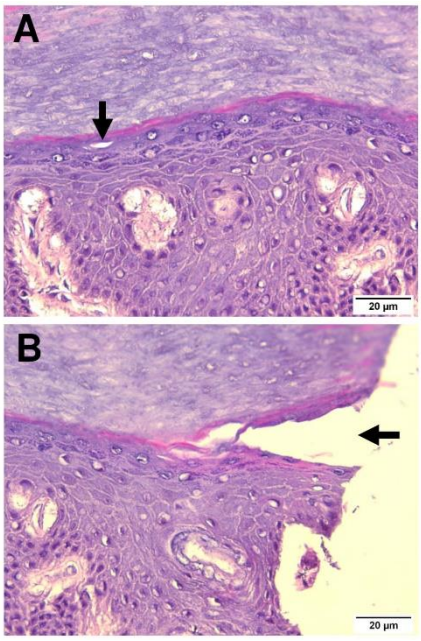


Figure 4

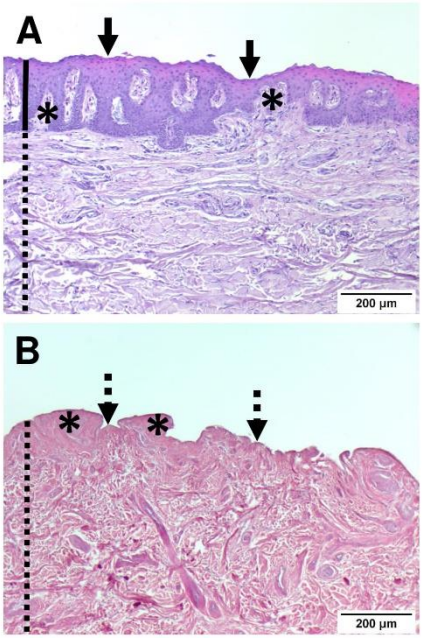


Figure 5

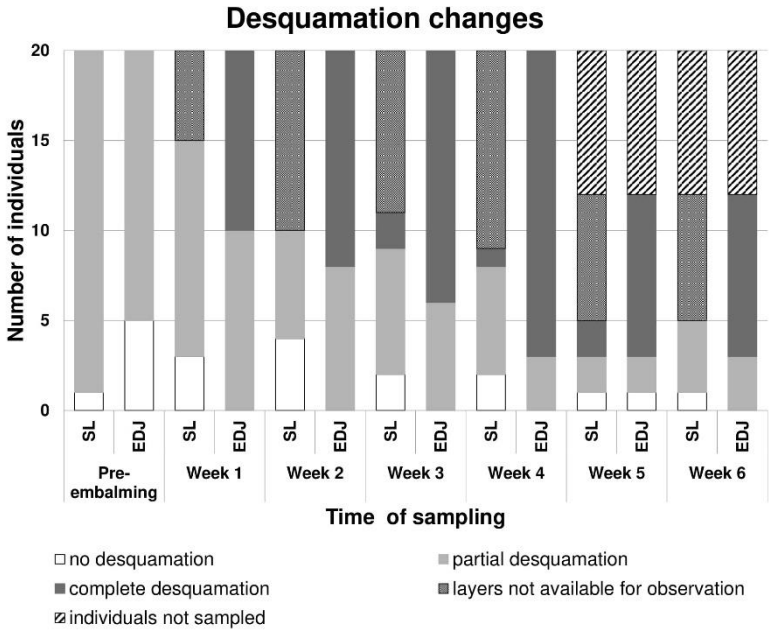
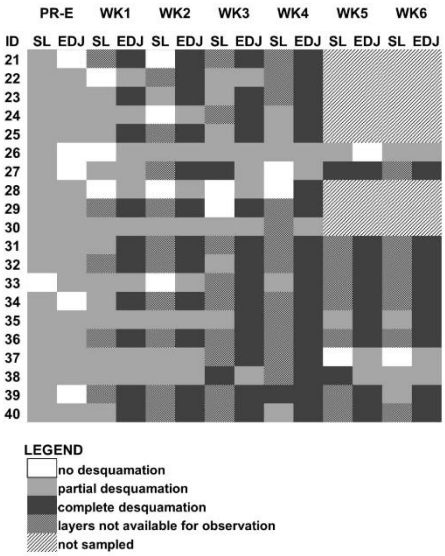
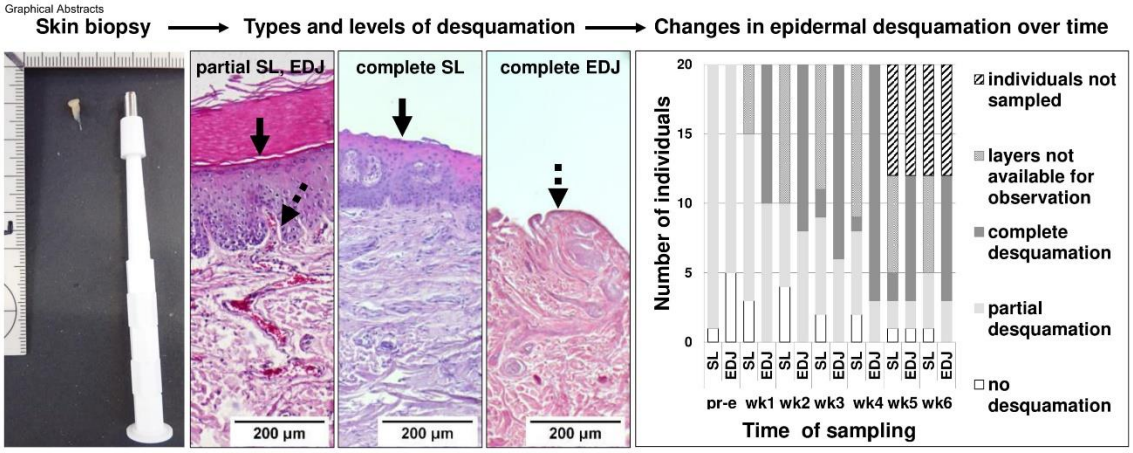


Figure 6



Graphical Abstracts



Ethical statement

Ethical statement

All procedures performed in the study were in accordance with the ethical standards of the institutional research committee and in accordance with Scottish legislation (the Anatomy Act 1984 and the Human Tissue (Scotland) Act 2006).

funding statement

Funding

This research was conducted as a part of doctoral degree training funded by Engineering and Physical Sciences Research Council.

Highlights

Highlights (limit: 85 characters including spaces)

- Epidermal desquamation occurs during the fixation of a body in Thiel embalming fluid
- Epidermal desquamation was observed to occur at two skin levels
- Partial and complete epidermal desquamation were observed at the two skin levels
- Complete desquamation at the epidermal-dermal junction occurred in 37 out of 40 cases